EXPLORATIONS OF THE COGNITIVE PROCESSES IN DESIGN**

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ABSTRACT

Intuitive design, as carried out by architects, product designers, and some engineers, is analyzed as a problem solving task within the framework of an information processing theory of cognition. A study of intuitive design processes was carried out utilizing four protocols as experimental data. Two of the protocols are presented in this report in their entirety. From the protocols were identified the information used, the transformations carried out on the information, and some of the administrative processes directing particular sequences of activities. Analysis of the protocols led to an operational model of design and hand simulations largely replicating one protocol. Fundamental issues of design methodology are outlined. Of particular interest is the insight offered into semantic memory retrieval processes utilized by designers and the representational languages used in complex problem solving.

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INTRODUCTION*

Design is the name given to the broad class of problem solving activities carried out by engineers, architects, and others who generate a specification for some portion of the physical environment. As fields particularly involved in specifying man's environment, architecture and engineering supposedly teach design procedures to future professionals. But because little is known about the pattern of activities design involves, design education in these fields relies on case studies, where self-teaching of procedures is mandatory. Since little is known about the sequence of activities that produces a creative design and since its procedures are implicit and self-taught, design is considered an intuitive process.

Engineering design texts have traditionally consisted of collections of potentially useful design solutions (for instance, see Faupel, 1965). Recent interest in methods has encouraged some authors to include statements about the design process. They predominently endorse a sequence of activities of problem identification, data gathering, analysis, synthesis, and evaluation (Hall, 1962, Chapter 4) or others of similar detail. The most detailed descriptions of activities in engineering design divide initial design activities into determination of a need, identification of the relevant parameters and criteria, generation of initial concepts for plausible solutions, and preliminary evaluation of them in terms of physical realizability and financial feasibility. The suggested following activities involve careful evaluation of the design concepts and their detailed specification for production, maintenance, and distribution. Typically, useful techniques are discussed for each activity. (Asimow,

* The author is indebted to Allen Newell for his encouragement and valuable comments on this work.

1964, Chapters 3-6) The few attempts made to explicate architectural design processes have essentially duplicated those of engineering. (Elder, 1965)

New methods of design have also been proposed (Jones and Thornley, 1963; Coons, 1963; Alexander, 1964; Manheim, 1966). As alternative processes for the existing intuitive ones, they claim to be superior, if only because they are explicit and can be taught.

Lacking from design education is knowledge about how basic design concepts are normally generated and how different activities are integrated to produce an original product. Before significant improvements in the intellectual powers of designers and in design methods are possible, it first seems necessary to determine what comprise self-taught, intuitive design processes: their strengths and weaknesses; their relationship of discrete activities within a whole. Only then can the relative merits of alternative methods be evaluted.

AN APPROACH FOR STUDYING DESIGN

Design can be viewed as one type of problem solving activity. The processes for solving problems in other fields, such as chess (Newell, Shaw, Simon, 1958; de Groot, 1965); geometry proofs (Gelernter et al, 1960); puzzle solving (Newell, 1968); and musical composition (Reitman, 1964) have been detailed in a form allowing prediction, and occasionally, replication. (Also see Feigenbaum and Feldman, 1963; Kleinmuntz, 1966.)

These studies have relied on a model of human cognitive behavior describing the nervous system as the body's prime information processing mechanism. The model interprets man as acting on complex information as a single channel processor, transforming states of input (stimuli) into output (response). Memory has been interpreted as allowing temporally independent recall of various information inputs. What makes any problem difficult is the wide range of information that may contribute as input and the complexity of organizing the relatively unique combination of input to generate the correct response. These theorists have primarily relied on verbal behavior as a significant trace of the cognitive activities mediating between stimulus and response. (Miller, Galenter and Pibram, 1960; Berlyne, 1965; Fitts and Posner, 1967) Studies dealing with concept formation have rewardingly used this same information processing model. (Bruner, 1956; Hunt, 1962; Bourne, 1966)

GOALS OF THIS STUDY

This paper attempts to build upon the premises of the above studies in order to better understand the processing of information in design. It describes the results of an exploratory study of the intuitive processes in architecture and product design, using both subjects and a problem common to these areas. These fields of design are of particular interest because of their emphasis on self-taught procedures and creative solutions. It offers an operational model of cognitive design processes based upon these studies. By operational is meant a model allowing replication of observed activities. Such a model should also allow predictions to be made about a design based upon analyses of the activities which produced it. The model leads toward a computer program that can simulate the general cognitive processes of design and also those of particular designers. Computer simulations would allow objective comparisions between existing and proposed alternative design processes.

The following study of these processes is made in three parts. The first part consists of the analysis of an already available case study report of a large scale architectural problem collected by Bassange, Kutch, Morgan and Varey (1966). This first analysis is circumscribed; its purpose is to provide hypotheses for a more detailed analysis. The second part explains the means used to collect four design protocols using experimental procedures. It includes a preliminary analysis of those protocols. Part Three presents a detailed examination of the collected protocols leading to an operational model of the observed design activities. This section ends with several hand simulations of the activities described in the experiment and produced by the model. It also summarizes the results gained and suggests issues for further study.

PART ONE

A BACKGROUND STUDY

Design, like other problem solving activities, can be considered as a transformation problem. Beginning with an initial information state, the task is to transform it into an acceptable solution state (Reitman, 1963). A design problem usually is initiated with some information about the initial transformation state. In architecture, information is often given about the site, money available, functions and tastes of the people the building will house, as an example. Some information is also given about an acceptable solution state: partial information about rooms, the finished site, and possibly materials, along with the assumption that the final state must respond in some undefined way to the existing functions and tastes of the people involved. From these goals expressed in a partial specification of the initial state and the final one, the designer develops a complete specification of the final state, e.g.,the working documents describing the construction of a building.

The initial orientation for studying this process was gained by re-analyzing an existing case study report of an architect working on the preliminary design of a large civic center complex.* This re-examination provided initial hypotheses about the cognitive activities for gaining a solution state, the information used, the organization of that information, and suggested more specific issues for study.

This case study related the activities carried out in generating an entry for a design competition. The winning entry would receive the commission for complete architectural services for the project. In such

*(Bassange, Kutch, Morgan, and Varey, 1966) This author is grateful to the authors of this case study for allowing its use here.

competitions, a program of space requirements, including room areas and circulation needs, are given along with basic site information. An entry consists of a conceptual level design presented in plans, elevations, and perspectives, but without construction details.

Because of the unique context of design competitions, the details related in this report differ from what would be expected in a client oriented situation. The log of activities was made by the chief designer of the project, who entered his own activities only, twice daily. One other person contributed to the project. Because the report only relates one person's design activities, the insights it allowed were, at best, hypotheses about the common information processing activities in design.

The basic assumption of previous cognitive and problem solving studies is that human information processing is a dynamically structured sequential activity. Problem solving and concept formation activities proceed serially, with a sequence of operations acting to transform one state of the problem into another. Transformations are directed towards a particular state, representing a solution to the problem or attainment of the concept. The approach for analyzing this report, then, consisted of describing the activities it related in terms of operations acting upon an information structure. While it was originally hoped that operations as primitive as simple arithmetic and binary logic could be utilized, the level of detail reported in the case study precluded such fine analysis. More global operations had to be utilized.

The operations were expected to act upon an information structure organized around design goals that were given or were determined by the designer, since the abstract organization of a problem intuitively suggested that goals were the primary given information. Such an organization has been proposed by Jones (1963), Norris (1963), Archer (1965) and Alexander (1964, pp. 66-70). But few examples of this type of transformation were found. Rather, the designer was continually working with "things", with physical aspects of a solution. Determining what the operations acted upon was a significant contribution to an understanding of this designer's efforts.

As it was possible to analyze this case study report in several ways producing different hypotheses, more than one analysis was originally made. (An earlier interpretation is given in Eastman, 1967.) The interpretation presented here is the one out of several that uniquely allowed elaboration, verification, and seemed to lead towards a working theory of design. Because this analysis represents only a set of hypotheses for further study, detailed derivations are not attempted here. Those interested in the derivations of the presented hypotheses should refer to the transcript of the report and its analysis presented in Appendix A. Further insights came from a graphic analysis, also presented in Appendix A.

HYPOTHESES GAINED FROM THE CASE STUDY

The architect's report did describe a serial process that included those tasks normally attributed to design. That is, activities were found that could be interpreted as problem identification, data gathering, analysis, synthesis, and evaluation. Yet the report certainly could not be organized according to such activities. Where these types of activities were observed, they were highly intermixed with others which have not hereto been identified. Another organization was found that did allow sequential organization. This organization classified the observed design activities in terms of Identify, Generate, and Integrate. These operations are assumed to be rather high level descriptors, each of which represents a whole series of more detailed processes. What made these operations discernible was their consistant organization around different aspects of the problem. A room, the structural module, the visual image, and fenestration are examples of the aspects of the problem separately treated by them. It was these "things" around which the activity sequence was ordered. Because of the centrality of these physical aspects for the overall process, they were given the name Design Units.

DESIGN UNITS

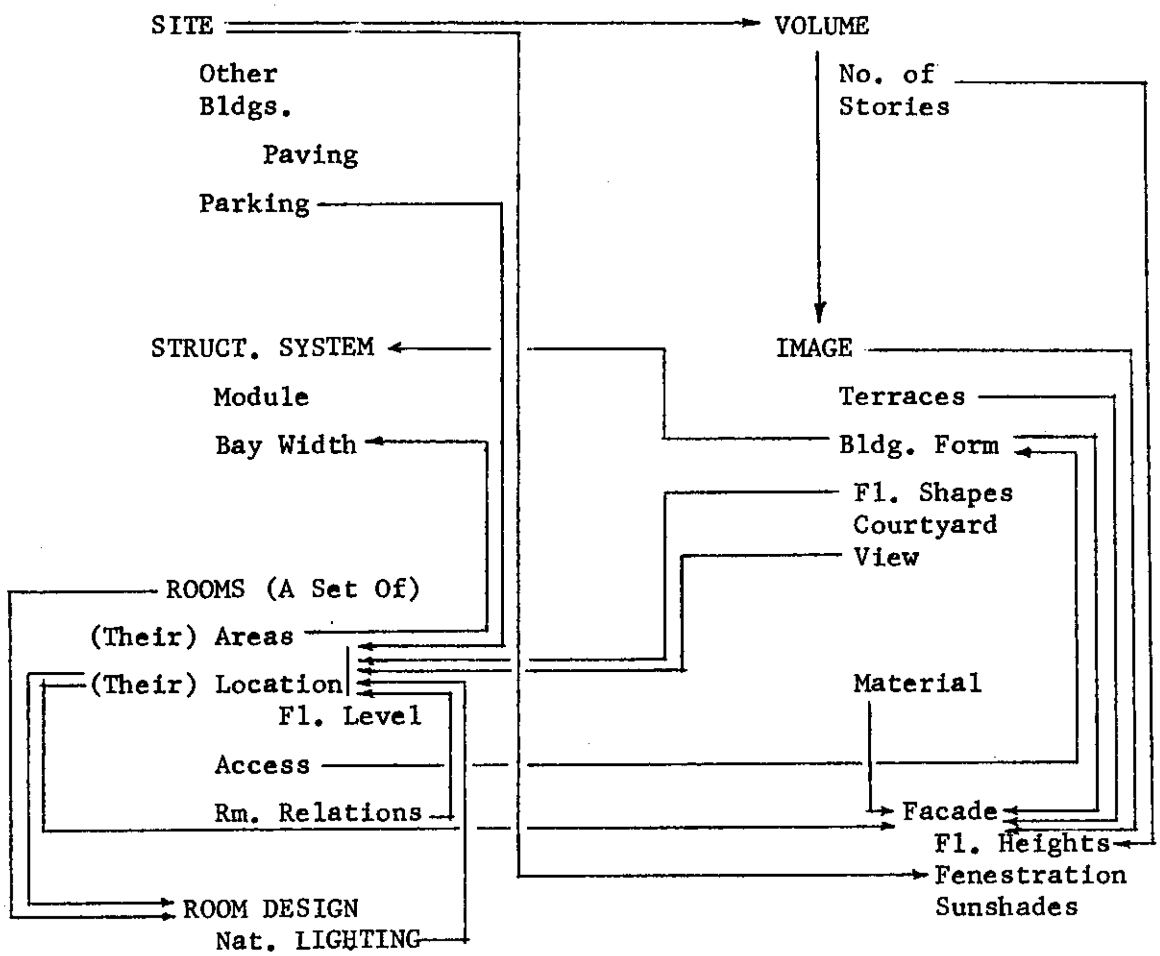
Some Design Units were given in the problem statement, i.e., all rooms, their areas and future uses of the site. The designer contributed others, such as facade, visual image, and fenestration. Each such entity was identified on the assumption that it was an inherent aspect of any solution. They seemed to represent general concepts identifying physical configurations associated with the problem class, in this case with "civic center". Because the architect utilizes Design Units defined by others and can integrate those he defines with them, it seems that Design Units are part of the culturally accepted definition of the problem class.

The Design Unit evidently is a heuristic device for quickly structuring a design problem towards a solution by relating design goals to physical forms. Given any set of goals to be achieved by some combination of physical configurations, an almost unlimited realm of possibilities exists.

Without assuming some particular Design Units initially, the solution realm includes all combinations of every physical configuration known to man. In utilizing DUs, a designer makes some assumptions about what configurations will likely fulfill the given goals. This seems only possible because the goals have been classified into a problem type defined by such terms as "housing" and "commercial offices", in architecture, and by such terms as "rapid transit" or "structural system" in engineering. In each case, a class of solution configurations are directly available. The Design Units used in this problem concerning a civic center are shown in Figure I. When acted upon, Design Units are considered in a serial order.

When a Design Unit (DU) was being considered in the report, what seemed to be taking place was that information gained earlier was being used to refine the DU's form. As information was gained about the problem, from the given program of requirements, from the designer's search of his memory, or from his search for an acceptable configuration for some DU, it was associated with the DU(s) it constrained. The information used in this refinement included attributes the DU should possess, such as area or dimensions; it included the components of a DU, (the components can also be considered DUs); it also included the spatial or visual relations between DU's. Because any such information delimits the range of specific forms a DU may take, each was called a <u>constraint</u>.

The designer seemed able to produce a specific form for a DU, e.g., resolve it, at any time. The form generated responded to some or all of the constraints associated with it. The goal of the designer's task was to identify a specific form for each DU that fulfilled all the goals of



THE SEMI-HIERARCHICAL STRUCTURE OF DESIGN UNITS

Each arrow represents a recognized constraint between Design Units. The direction of arrows represents the direction of influence as expressed in the final solution in the report.

FIGURE I

the problem. The problem was difficult because the resolution of any one DU added new constraints to other DUs. A particular configuration of one DU had to be spatially related to the others. In the report, room areas had to be disjunct; all rooms within an exterior form had to completely fill that form. Also, particular relationships between DUs were desired, either for functional or esthetic reasons. Thus the resolving of any DU into a specific form delimited the relationships possible and generated new constraints for other DUs. Those aspects of the problem resolved early in the process constrained the possible form of DUs resolved later. For example, the first visual image configuration proposed in the report located the Council Hall in such a way that it so constrained the location of the entrance and other rooms as to make it impossible to meet given constraints concerning human circulation. Later, the image configuration was altered to allow fulfillemnt of the circulation goals. (See Appendix A, No. 22.)

Because some constraints were given and therefore difficult to alter, while others were determined by the form of resolution of a DU and could be changed by generating another alternative configuration, it was useful in the report to differentiate between these two types. They were called goal constraints and internal constraints, respectively; the latter gaining their name from their derivation, which is internal to the problem organization as developed by the designer.

The DUs for this problem were resolved serially, one at a time. A variety of sequences was possible. When conflicts arose out of the information gained from a sequence, reiterations of portions of the sequence were required. Intuitively, the particular sequence chosen would seem to affect both the freedom with which the designer can resolve some DUs and the number of reiterations required in the process to satisfy all constraints. The particular sequence chosen, then, seems to play an important role in determining the form of a solution and the efficiency with which it is reached. The designer in the report seemed primarily concerned with visual image, and dealt with it early in any iteration of the process. Otherwise, little was suggested in the report of a conscious sequence of design resolutions.

The concept of a civic center and the given problem statement evoked from the designer a set of concepts, DUs, defining the physical configurations that were a part of any solution. With these he associated various attributes, component configurations, and relations as his understanding of the problem proceeded. Not only was the total problem divided into DUs, but identified DUs were sometimes broken into more detailed component DUs. In the report, facade included fenestration and sunshades; structural system included bay width. The organization of DUs was sometimes hierarchical. This is not to say that DUs were organized in a neat set theoretic structure. In the report, room location determined room design, which in turn determined the amount of natural light. But when that amount was not satisfactory, the desire for lighting sometimes affected room location. The multifaceted nature of the problem required several iterations through its different aspects, contradicting any simple hierarchical organization. Careful study of the considerations made by the designer showed that no hierarchical structure could encompass them, supporting the arguments of C. Alexander, presented in his paper, "A City is Not a Tree" (1966). Along with the DUs considered by this designer and their attributes shown in Figure I, are the relationships identified and their direction of influence.

OPERATIONS

Design Units provided organization to the information on which the designer acted. The earlier mentioned operations of Identify, Generate, and Integrate acted upon this structure to sequentially elaborate and refine the DUs comprising a potential solution.

The Identify operation consisted in recalling information about a particular DU, or a specific configuration of that Unit, from memory. On one occasion it also consisted in looking for information in the public library. Thus, it must be assumed that Identify can be an operation carried out on either an internal or external store of information. It was difficult to determine from the report if information was retrieved in any already structured form, that is, already associated with a DU, or if an aspect of the Identify operation involved searching for the relevant Units with which to relate the information. Only the analysis of more detailed reports can resolve this issue.

Generate created a particular physical configuration for a DU. It thus involved a retrieval operation similar to Identify, but also included a discrimination of a particular configuration from among all those that could be potentially generated by the designer. Again, because of the lack of detail in the report, it was impossible to determine the basis for the selection process. One possibility is that the designer's past experience is so structured that the vividness of a particular configuration of a DU is determined by his subjective experience with it. Thus, by simply retrieving the first one that he can recall, a natural selection process takes place. The original encoding of the situation, whether it was functionally or emotionally interpreted, determines the likelihood of its recall. Current hypotheses concerning memory decay would suggest that recently experienced configurations would be more likely to be retrieved than others. In the report, the designer's emphasis on recently publicized building images suggests this kind of mechanism.

Integrate combined a potential configuration of a DU with others already resolved. It involved spatially locating an alternative and applying the identified relational constraints to test the acceptability of the particular integration. Several locations might be considered. Failure caused a reiteration of earlier parts of the process.

The report also included operations called Receives and Choose. Receives denotes a DU, constraint, or alternative configuration imposed upon the designer. Chooses involves the selecting of a particular configuration when none respond to all constraints. It seemed to represent a compromise accomplished by trading off constraints in place of reiterating earlier design decisions.

Because the organization of DUs was sometimes hierarchical, several component DUs were sometimes Integrated into a higher order one which in turn was Integrated into a solution. Thus several levels of DUs may be hierarchically Integrated with few or no Generate operations above the most detailed level. Recursion of this kind never went beyond a second level in this architect's report. Only those recursions were made that were necessary to allow a particular configuration to fulfill an identified constraint.*

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* It is recognized by designers that a huge recursion of DUs is thus possible, eventually regressing into metallurgy and chemistry for considerations. Rigorous design naively is assumed to require the maximum recursion possible, so that the largest search realm will be explored. A few attempts at such recursions have convinced more than one designer that unselfconscious, intuitive design is the only one possible.

Because the Integration of other alternatives into a partial solution implicitly produced new constraints related to other DUs, Identify was often an implicit operation. Also, because a particular alternative configuration may not satisfactorily meet its constraints, a series of Generate or Generate-Integrate may follow an explicit or implicit Identify. Lastly, the series of operations for one DU were often intermixed with others. The designer would temporarily turn to the issues of some other DU when he could not satisfactorily Generate or Integrate any one of them. The sequencing of these operators is best seen in the graphical analysis in Appendix A. The general sequence of operators for any one DU was Identify-Generate-Integrate.

Evaluation of each specific configuration of a DU took place twice during this process. It took place during the Integrate or Generate operations producing an alternative for a DU. It also took place during the Integration of that alternative with others. The typical form of evaluation was a binary test, acceptance or fail. Because each evaluation stage encompasses several non-relatable criteria, and because no a priori relation can be made between manipulated variables and criterial ones, the process bears little similarity to decision theory models of design decision-making. (See Starr, 1963.)

GENERAL IMPLICATIONS

A recognition derivable from the protocol was the designer's emphasis on spatial constraints. From a day by day tabulation of the distribution of time spent dealing with various constraints, spatially relating and integrating the problem involved approximately fifty percent of the designer's time. Approximately thirty percent of the remaining time was spent on visually coordinating the solution (i.e., in esthetics). These emphases denote the aspects of design with which this architect was most concerned. It is likely that most architectural problem solving reflects a similar emphasis. It is with the spatial considerations that architects seem uniquely trained to deal. Similarly, traffic flow is assumed to be the major concern of transportation engineers, structural rigidity the major concern of structural engineers. Each design profession, it is suggested, is predominantly concerned with a particular set of DU's and particular types of constraints. Because some design fields are concerned with the constraints between certain DUs which are well defined in quantitative relationships, while others are concerned with ill-defined constraints which are left to the subjective evaluation of a designer, as in this case, the overall task and approach of different types of designers, such as architects and engineers, seem disparate. Yet this protocol compares favorably with the approaches of engineers when the form of constraints is ignored. (Jerger, 1960, Chapter 10; Meister and Farr, 1967)

The analysis of design problem solving in this report, when compared with analyses of other types of problem solving activities, suggests several ways in which design problem solving is unique. The types of problem solving previously analyzed, such as crypt-arithmetic, missionaries and cannibals, or logic proofs, have involved obvious sets of possible transformational states. The rules for achieving various states were also well known. The rules of addition, subtraction or logic, their truth tables, and the range of alternative integers possible between given limits are immediately available from the memory of most members of adult Western society and thus can be ignored as a task of problem solving. These studies have emphasized the process by which the rules for achieving various states are efficiently applied to reach a solution. They have thus been concerned with means of efficient search of an a priori realm. The information search and retrieval processes for defining that solution realm have not been considered.

This report indicated that the same is not true for the information utilized in design. No set of alternatives has been formalized to define possible states of a design problem. Because alternatives are empirical and not formal, even an exhaustive trial and error search would be impossible, not only because of the time required, but also because the possible states could not be generated. Moreover, the rules for evaluating a state are not readily available. Thus, similar to chess, design involves a search for appropriate criteria, a search not formally aided by the conceptual organization of past experience. (The only conceptual organization aiding this designer was the hierarchical organization of some DU's. Yet, because these consisted of conventions concerning the present organization of the environment, they were informal and would likely vary between designers.) Yet in all other ways, problem solving theory proved to be a useful conceptual tool in understanding intuitive design.

In summary, the design process, as seen in this one report, consists in the formation of an information structure organized around physical aspects of the problem, around Design Units. These DU s were retrieved from memory as intrinsic components of the general problem "Civic Center". Associated with each is the relevant information concerning it, its significant attributes, how it interacts with other DUs, and the range of configurations it represents as a class. Components of DUs were also identified. The organization of DUs was semi-hierarchical.

The primary operators acting upon this structure are Identify, Generate, Integrate. They serially: Identify a relevant Design Unit or one or a series of constraints; Generate a possible configuration from within the class of Design Units that fulfills the constraints relevant to that Design Unit; and Integrate this configuration with others already chosen in accordance with various relational constraints. Two kinds of constraints were identified: goal constraints given in the definition of the problem; and internal constraints imposed by the particular form of the solution taken. The sequence in which parts of the information structure were treated seemed to be determined by some complex "Administration" process that controlled its overall direction. No significant information was gained concerning the means by which this particular designer directed his process.*

HYPOTHESES FOR FURTHER STUDY

In detail, the report offered the following hypotheses.

One: Problem solving processes in design operate on an information structure nodally organized around concepts defining physical configurations. These processes ignore information not related to some such entity. (Thus design does not proceed from a defining of attributes to the deduction of an object meeting those attributes.) Design information only

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* That this designer conceptually organized his problem around, particular Design Units does not mean that there is only one set of Design Units that can be used to organize a prpblem. Much of the theoretical effort in design and planning concerns a debate over the relevance or irrelevance or particular Design Units. (Webber et al, 1964; Meister and Farr, 1967)

allows some more generally defined entity to be more specifically defined.

Two: Design operations can be depicted as acting upon portions of the above information structure. General types of operations include: the identification of new information and its integration within the structure above; the generation of a specific example of an entity that fulfills the attributes attached to it; and the physical integration of the entity with others checking to see that relational constraints are met.

Three: The sequence in which entities are considered and in which operations are applied to them is determined by an administrative process. Wide variation probably exists in this process, producing some of the variety expressed in the results of designers.

Other issues of importance were not considered in this initial study. No study was possible of the details of spatial manipulations. Though emphasized in the content of the report, the lack of graphics and reliance on written materials gave little impression of how the designer worked with space. Because the report did not mention the media used in resolving aspects of the problem, little also could be determined about this potential influence. Did working in plan or section or perspective influence the designer's solution? What other type of representations did he utilize? Also, what is the process by which information is retrieved from memory? Are there a variety of strategies for remembering information relevant to design such as DUs and constraints, or only one? If there are more than one, what is the worth of each?

These issues and hypotheses will be examined in detail in the following design experiments.

PART TWO

EXPERIMENTAL RESEARCH IN DESIGN METHODOLOGY

Verification of the first hypothesis, concerning the organization of design information, requires detailed examples of the information retrieval and processing activities of designers. These examples should show not only the centrality of physical configurations in the designer's concept structure, but also the organization of the associations related to these configurations. Verification should show the DU and its associations, whether retrieved from memory in this form or composed after information retrieval, as the major unit upon which transformations are made.* This hypothesis would be rejected if gained evidence showed significant portions of designers' information processing activities organized around some other information structure.

Incorporated into this hypothesized information structure should also be the spatial and metric information required to represent any specific configuration of a DU three dimensionally. In the study presented in Part One, the only trace of activities available was the written report. From a written report, it was quite natural to translate DUs and the information about them into a linguistic structure of entities (DUs) and attributes. But it was also clear that the original operations carried out by the designer did not act on such a verbal organization of information, but rather on sketches and drawings. Since the mode of information used in a problem may influence the kinds of processing that take place, the representation of information, in both external representations and

* It is implied that man's knowledge of the world can be represented in a similar format. Support for such an implication is made by Hempel (1956).

a S's memory, may significantly influence the generation of solutions. This issue has commonly been ignored in problem solving and cognitive theories and experiments. (For an instructive exception, see Paige and Simon, 1965). The processing of information in design problem solving can only be thoroughly understood when the normal modes of representing design information are taken into account, along with the transformations that can act on those representations.*

Another major hypothesis gained from the case study dealt with the form of operations acting upon retrieved information. Three categories of operations were originally proposed: Identify, Generate and Integrate. Only the general composition of these activities was suggested. Detailed analysis of design activities should reveal whether these operations are utilized by other designers. It should also suggest the detailed composition of such operations. Also requiring elaboration is the relationship of these operations to the various kinds of information used in design, such as numbers, words, and drawings.

The last hypothesis concerning the administrative operations directing the design process can only be detailed in conjunction with the previous two; any changes in them will alter the last one. Presently needed is a schema within which hypotheses about administrative operations can be proposed - how such operations might work and vary between individuals in both their singular operation and in their overall organization. One aid

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* The intellectual processes involved in mathematics and logic can be thought of as the development of transformations for particular information that has been represented in a specific way. While these are formal transformations, it is implied that man is involved with many others, including language (whose transformations are beginning to be understood (Chomsky, 1965; Katz and Fodor, 1965)), and all forms of signs and symbols (Morris, 1946). The graphics of the designer can be thought of as another language with its own transformations.

in the development of such a schema is the successful preliminary studies of administrative type processes for other types of problem solving made by Newell (1967).

An experiment was designed with these hypotheses and issues in mind. Because the information structure and operations in design are intimately bound up in the issue of the representation of three-dimensional objects, a simple problem involving spatial organization was chosen. The information about the problem was presented in a variety of media so that the relationship between operations and the representations they act on could be better discerned.

THE EXPERIMENT

The paradigm upon which the experimental procedure is based is similar to that used for other problem solving experiments. A problem is presented to a S in a well controlled format. The S attempts to solve the problem and express his thoughts while doing so. The expression of information by a S in verbal or other form, as he is transforming the input stimuli into an output, is considered a significant trace of the actual mediating information between stimulus and response. By analyzing the expressions made, insight into the information processing carried out by problem solvers is gained. (deGroot, 1965, Chapter 8; Newell, 1968)

The experiment consisted in the presentation of a small, rather common, design problem to a group of experienced, intuitive designers in a controlled situation where activities and responses could be carefully monitored. The problem required the redesign of a bathroom for a developer built house. Each S was requested to verbalize his thinking as he solved the problem; that is, to think out loud. The S's actions were monitored and recorded by the experimenter (by taking notes) and his verbal behavior was recorded on magnetic tape. All notes and graphical representations of the problem were also collected.

The design problem given was somewhat open-ended. Certain information that the S needed for a solution could be asked for from the E. By this means, it was hoped that the manner in which each S identified and structured relevant information would be more than normally externalized. The problem statement given to each S at the beginning of the experiment is shown in Figure II.

Each S was tested individually and worked at a drafting table with the E sitting at a desk nearby. The S was provided with drawing tools and several sheets of tracing paper, some with the existing floor plan printed on them. Information about the problem was presented in three representational forms: in writing, a photograph, and a plan view. He could also gain additional information in a verbal form. The E responded to questions concerning the problem by offering predetermined details concerning the questions asked. The time allowed to complete the problem was fifty minutes. Each S was reminded of the time as the experiment proceeded.

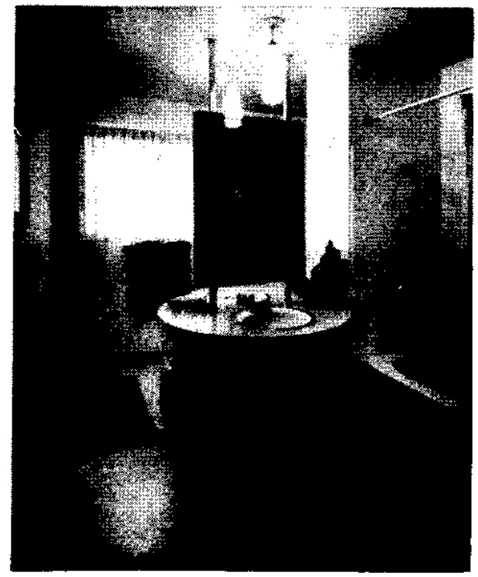
The Ss in this experiment, by orienting their verbalizations to the E, quickly seemed to forget that the situation was "artificial". When two new Ss were later asked to replicate the experiment, but without any monitoring, the results were similar to the experimental ones. In some cases limited interaction with the test monitor seemed to provide extra motivation for producing a carefully examined solution.

EXPERIMENT NUMBER TWO

The accompanying plan and photograph represent an existing bathroom plan for one model of a home sold by Pearson Developers in California. This model of house has not sold well. The sales personnel have heard prospective buyers remark on the poor design of the bath. Several comments are remembered: "that sink wastes space";"I was hoping to find a more luxurious bath". You are hired to remodel the existing baths and propose changes for all future ones. (these should be the same)

The house is the cheapest model of a group of models selling between 23,000 and 35,000. It is two stories with a ranch style exterior. The bath is at the end of a hall serving two bedrooms and guests.

You are to come up with a total design concept. The developer is willing to spend more for the new design -- up to fifty dollars. For all other questions, Mr. Eastman will serve as client. He will answer other questions.



Jon Meacham

A round vanity makes the most of a square-shaped bathroom

It permits two lavatories in a minimum-size countertop. And it also lets two people use the sinks at the same time without getting in each others' way. Extra shelves are set between the lower cabinets

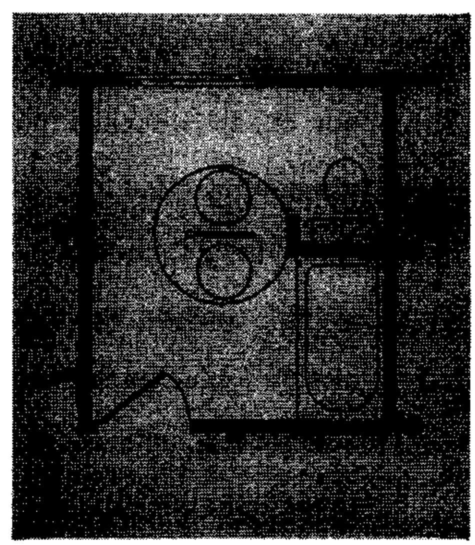


FIGURE II

Several days before the experiment, the Ss were told that they would be given a design problem dealing with bathrooms. They were asked to think about this type of problem so that they would be prepared to deal with it. From this forewarning, it was hoped that the Ss would have a "set" similar to the normal designer who may "mull" a particular problem in his mind for long periods before generating a solution. (In preliminary trials of the experiment that did not include any forewarning, S's commented that this was a necessary condition for normal intuitive design.) They were also told that they would be asked to "think out loud" and that the purpose of the experiment was to find out more about "how designers solved problems".

The subjects whose protocols are described here were four graduate students enrolled in an interdisciplinary design program at the University of Wisconsin. Their ages ranged from twenty-five to thirty-two. By background they included two industrial designers, an urban designer, and an interior designer. All Ss had some professional experience; the two industrial designers had more than five years. All had been through an educational program relying on intuitive, self-taught design procedures. From any point of view, the Ss would be considered competent, perhaps outstanding, designers in their respective fields.

RESULTS

Within the experimental situation, the Ss richly varied in their processing of the problem information. Because the preliminary analysis in Part One and these protocols expressed many different and complex activities, and because of the open-ended nature of this experiment, operational descriptions will not be directly attempted in what follows. Rather, a first preliminary analysis will distinguish what information is used by the Ss in solving the problem. It will also attempt to determine the processing capabilities of these Ss - of their means for relating and transforming this information. Further analysis in the following section will develop operational mechanisms for replicating these capabilities. The next section also presents evidence of a positive or negative kind for the hypotheses already presented.

For this exposition, almost complete excerpts from two of the protocols will be given. (Only clearly redundant expressions have been deleted. Deletions are noted by ....) These will be augmented by limited excerpts from the other two. After a basic description of information transformations has been presented, a comparison of the protocols in terms of some of the presented issues will be made. To begin this analysis, two representative examples of the beginning of a protocol follow:

PROTOCOL ONE: BEGINNING

PA 1: "An objective is 'a more luxurious bath'... 'A total design concept'... The list of comments remembered were 'wasting space' and some opposite of luxurious. Whoever wants these to be redesigned considers these are the most objectionable.

PA 2: One reason that it doesn't have a luxurious quality, I think this

(1) (2) (3) (4)

FIGURE III

would look rather small. In this picture it looks very spacious, but it must have been taken from outside of the room in the hall. When you get into this thing you're about four feet to the sink, standing in the door....

PA 3: I think I would juggle the drawings here on a piece of paper. It seems that there are no objections with how this thing functions, left out storage space, etc. - - All the necessary utilities, toilet and so forth, have been included. Evidently, they're of a decent size.

PA 4: If there are problems of space, and I think there are, in looking at it, it would largely be a case of juggling it around. There is wasted space in this design. In between the toilet and the washbowl and the tub and washbowl. These are inconvenient little spaces that can hardly be used.

PA 5: Something that's sort of superficial, this seems to be a rotating device. (The counter) I have an uneasy feeling about it.......

PA 6: Another thing that wastes space is the toilet facing the wall, which means that you have a block space in here, which, if the toilet were facing this way (i.e., into the room), the space would become part of the larger space out here.........I think what I would do in this case is start juggling the fixtures and sketch of the room - -. When such a situation comes up it means many little drawings.

PA 7: (The S proceeds to make tracings of each fixture and of the outline of the room.) I'll assume a washbowl is about that big........

PA 8: First, I would try and arrange all three; washbowl, tub, and watercloset along this wall, which might be a little crowded...(He makes sketches that sequentially develop as shown in Figure III (1-2).) You have a lot more space - - open feeling to it......You have one washbowl and it's crowded. It does retain all the plumbing on one wall....this is going to boil down into making a lot of sketches and thinking most seriously about what exists and criticize and repair [it].....This thing next to the tub would be crowded.

PA 9: (He rotates the tub, then completes an arrangement as in Figure III (3-4). I'm trying to make an arrangement of toilet, two sinks and tub, with plumbing on one wall - without coming out into the room. Not only to save plumbing, but also to leave a large open space. So far, I feel these arrangements would be cramped."

PROTOCOL TWO: BEGINNING

PB 1: "One of the comments - - the purchases made was that they hoped to find a more luxurious bath....I'm also wondering about the two sinks. I'm wondering why the person looking at it said that the sinks....waste space. This photograph is deceptive in that it looks larger than it is. Storage space looks cramped by putting it all in one cabinet.....

PB 2: I've been thinking abour the problem and have come up with a few parameters that are important to consider. This is a problem where the people said this is something they didn't like. What you're - - going to look for first is why....there is a logical reason for their not liking it.

PB 3: The thing sits out here. It doesn't give an impression of space. There isn't any space in the middle....

PB 4: Some other things I've been thinking about concerning bathrooms in general [is] privacy, for the toilet area, and for the shower or bath. Especially if we're going to have two sinks....for more than one person... If we're going to create a feeling of more space....we're going to have to create an area which appears open.....

PB 5: I want to play with this scheme where I try to open up just certain areas and utilize the rest of the space for more storage. This is what's lacking....

PB 6: Some of the parameters I've been thinking.....is this aspect of temperature. Not the actual temperature....This is possibly one thing a luxurious bathroom does....it has a warmer feeling about it. Perhaps texture and floor covering are an influence.

PB 7: Another thing is privacy....Another thing is cleanliness, or sanitation, freshness. A bathroom, because of so much use of water, and the toilet, it seems a problem of cleaning. Storage, and I think especially the points of storage. Towels- - should be [stored] in the bathroom - - same with the toilet paper. And the special needs of women around the toilet area....

PB 8: You have a window you don't want to cut off in your attempt to get privacy. You have two sinks for multiple use, which requires more privacy, too.

PB 9: (Draws sketch as in Figure IV (1).)....perhaps we could devise some way for providing privacy for the toilet and bath. (Draws Figure IV (2).) We have only a five foot tub. That is generally too small....this could handle sink and storage nicely. (Draws Figure IV (3), erases then (4).)... back in here against the window.....There are two areas making a demand on towels. They could be placed closely together. One and a half foot counter. (Then draws Figures IV (5-7).)

PB 10: Seven feet....doesn't provide easily accessible storage space. The shower is across the window - problem of water...the window and the door pretty well set off this area of the room."

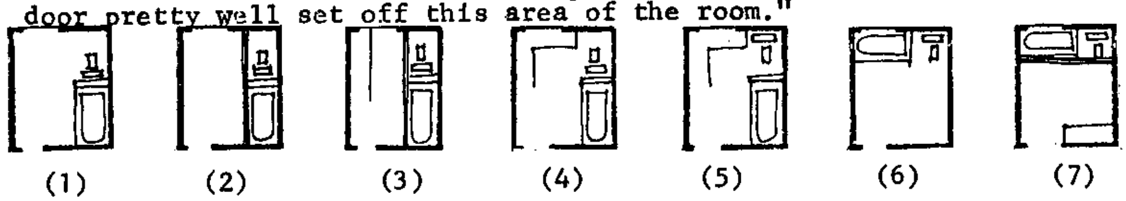


FIGURE IV

In these two protocols, as well as in the others, the Ss began by attempting to formulate a clearer definition of the problem. The generation of a better formulation was necessary; the given problem statement did not explicitly say why the existing design failed or what should be changed to improve it. To make a formulation all Ss relied on both given written and graphic information and their own experience with bathrooms. From such information organized in the appropriate manner both what part of the design to be changed and how it should be changed were evidently identified; transformations were soon initiated.

The first S relied almost completely on the given information to make his formulation. With the two criticisms of the existing design, "wasting space" and "some opposite of luxurious", he associated information perceived in the photograph, e.g., "looks rather small" and examples of wasted space. (PA 1 - PA 2) Other information is recalled from memory, i.e., the room's various functions,and is compared with information in the problem statement, e.g., "no objections with how this thing functions" (PA 3). He then identifies these specific aspects of the existing design that seem to have caused the adverse comments, the relationship of tub and washbowl, toilet and washbowl, and the spatial orientation of the toilet, after which he is able to begin transformations on the problem (PA 4, PA 6).

What this S can be interpreted as doing is to pragmatically associate the given verbal and graphic information with his own stored information about the use of each fixture. By associating the complaints with the graphic information he identifies physical aspects of the design that may have caused the comments. Then by searching his own memory for constraints related to those aspects, he is able to identify disparities between 'what is' and 'what ought to be'. These disparities suggest unfulfilled design constraints that can be interpreted as having produced the complaints. The given information directs him in a search of memory to produce these constraints. A schematic representation of the associational process is shown in Figure V.

The second S began by organizing information about the problem in the same manner as the first; he worked from the problem statement (PB 1-3). But after this initial tack, he turned to quite a different one. He began identifying from memory general information applicable to all bathroom designs. 'Privacy', 'ease of cleaning', 'storage', and 'texture' are all recalled as possibly relevant because of the type of design problem involved (PB 4, PB 6-7). It is significant that this information can be retrieved without any other cue than that he is designing a bathroom. The considerations the S retrieves from memory seem to be general attributes of bathrooms that affect the quality of their design. In essence, he retrieves potentially relevant constraints for this problem type.

Yet in order to apply them to the problem at hand, the S is required to identify where and how they are to be applied - to find a physical aspect of the design for which they are relevant. Thus, he goes on to express that "privacy" relates to the shower and toilet and that privacy is emphasized with the inclusion of two sinks (PB 4, PB 6-7). He perceives from the photograph that the storage space looks cramped (PB 1). He recognizes that two activities require storage (evidently, in the toilet and tub areas) and implies that the location of storage should respond to the locations of these activities (PB 9). He states that warm texture can be gained in the use of particular floor materials (PB 6). Each of

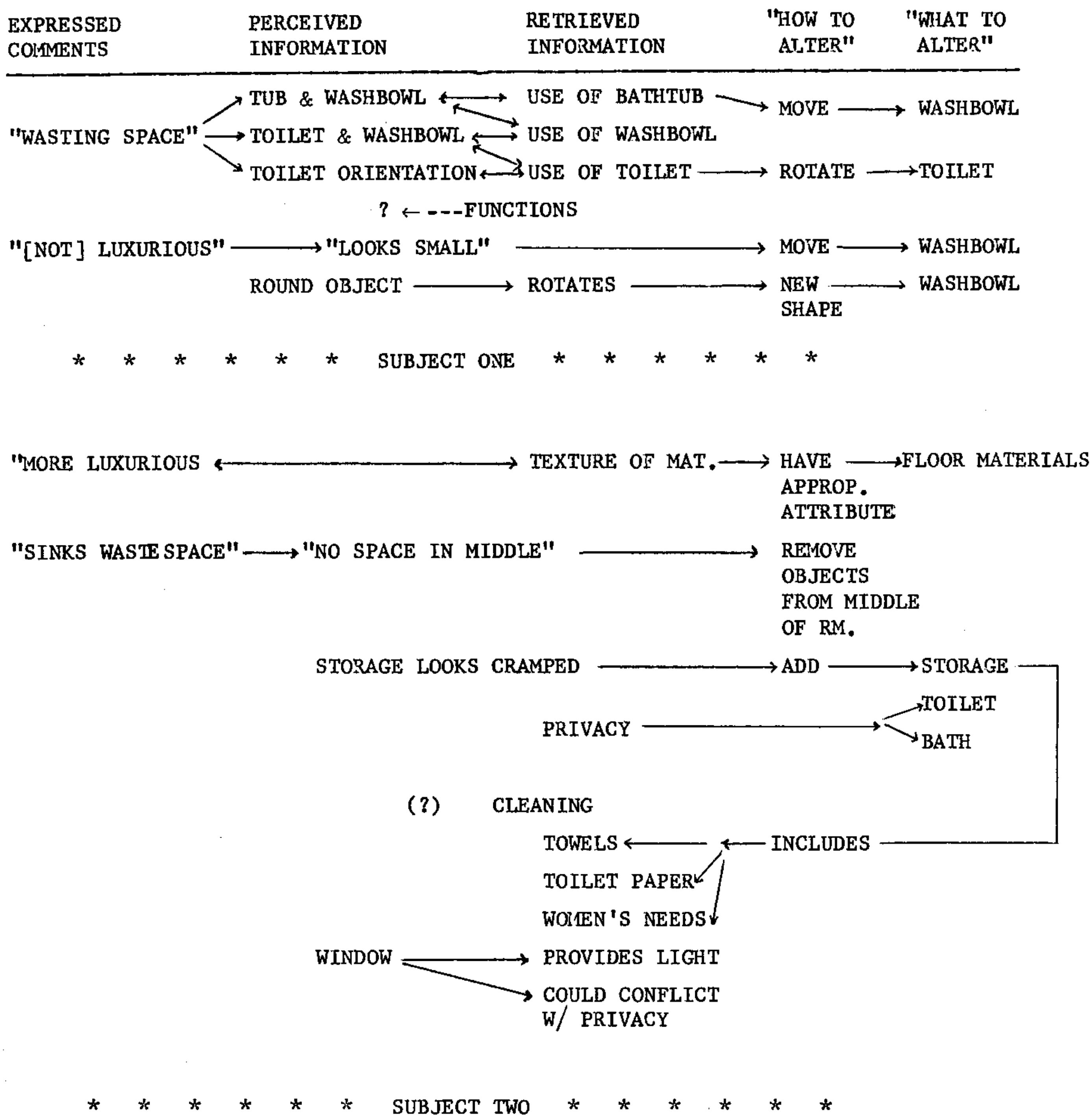


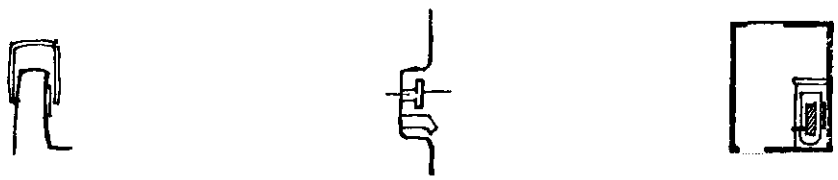
FIGURE V. Semantic associations made by Subjects One and Two at the outset of Experiment One. Arrows represent temporal sequence of associations.

these statements relates a constraint to some aspect of the bathroom design where it can be applied. In this case, constraints are first retrieved, then associated with information about the problem. Only those constraints so related are utilized. It is noteworthy that cleaning is never related to a physical aspect of the bathroom and it is never used as a consideration in his design. This S's associations are also represented in Figure V.

Both S's actions can be interpreted as attempts to better formulate the problem by finding some specific constraints, some information that delimits a solution, that have not been fulfilled. These constraints may be circumscribed, as in the case when only those that directly relate to adverse comments of an existing situation are considered (e.g., Protocol One). The other S's search for relevant constraints is broader based and includes all accessible information that relates to the general class of problem being considered. When the problem situation includes no existing design, it is expected that other examples of similar problems would have to be examined or that memory would have to directly produce possibly relevant constraints. Both techniques offer a means for gaining the necessary constraints.

Upon retrieval, these constraints are associated with some physical aspect of the design where they are applicable. In this problem, the entities to which they are to be related are given in the existing design. Bathtub, counter, toilet, etc. are already designated. If a problem did not explicitly give these, then the designer would have to retrieve them from memory also. Constraints not related to entities are never acted upon.

A variation of the second technique must be mentioned. Instead of producing information about bathrooms in a random manner, one S retrieved it in a highly organized form. Let us look at an excerpt from his protocol.



(1) (2) (3)

FIGURE VI

PROTOCOL THREE: MIDDLE

PB 11: "There is an important feature I want to build into the tub area. The plumbing fixtures should be flush mounted so that if you fall down, you won't strike your head on them. It would just be a box area in the wall here. (Draws Fig. VI(2))....

PB 12: I would put a non-slip surface in the bottom of the tub.

PB 13: Another thing, children and even adults have.....difficulty getting in and out of a tub. I want to include a hand device....here. (Sketches Fig. VI(2))....ideally there would be something on the other side...as well.. These things are available.... (Sketches Fig. VI(3).)

PB 14: How much more is tile? How much would it cost to tile just the bath enclosure? (Exp: Tile costs two dollars per square foot.)- - - I can't come close. How much is formica? (Exp: a dollar fifty). I know what-polystyrene sheets. Same material they mold refrigerator liners out of. Very inexpensive material. It's applied with the same adhesive as formica. It comes in any color and with a matt or gloss finish. It is prone to scratchin....You'd have to leave instructions not to use Comet - things of that nature. But the same is true of paint. Metals are expensive....I'd like to make an exhaustive search of wall materials. Other plastic materials - I'm thinking about maintenance on this tub, getting down and cleaning it.

PB 15: Ideally, the tub should be higher...If it's higher you have to make steps so that children and adults can get in..."

This S systematically generates constraints related to only one fixture at a time. Thus where each constraint is to be applied is determined by the sequence of retrieval. By this method of searching memory, a rich assortment of constraints are quickly generated for each physical aspect of the problem considered.

After constraints are identified and related to an aspect of the problem where they can be applied, the first two Ss initiate a design. In that each S has identified different constraints, their designs vary. In both cases, those parts of the design for which relevant constraints have been identified are those that are first manipulated. The first S begins working on a design that explicitly responds to them. (See Figures III 1-3.) Though he doesn't mention the constraint concerning 'plumbing on one wall' until after he has generated a first solution, it is evident that it, too, has been applied in his transformation (PA 8). Upon examining the results of his first action, this S applies two other pieces of information, the inclusion of two sinks, and a constraint for some opposite of 'cramped' (PA 9). The first proposal is rejected on these counts. Thus, after acting on the problem, an evaluation of its current state is made.

His next action is the one among the many possible that significantly improves the 'cramped' aspect of the design yet that still keeps 'plumbing on one wall' The bathtub is rotated so that only its end is against the relevant wall (Fig. III3). By common sense, the selection of this particular manipulation seems obvious. But the ability to find this action directly without trying many others first is an example of the insight available to designers; it indicates their capabilities for finding appropriate transformations that improve the status of their problem. The simplistic explanation that in his mental representation of the problem the S tried moving all fixtures in a random way until one was found that fulfilled the constraints is not acceptable. Random actions on three fixtures allow a huge number of possibilities. Guiding of the S's efforts was necessary to find this operation. Minimal requirements for this capability might be that the S only attempts to manipulate fixtures along the one relevant wall and that he possesses some priority system that would attempt to manipulate the bathtub relatively early in the sequence of possible fixtures.

Other manipulations utilized so far are the removal and relocation of the counter along the wall, the rotation of the toilet, and the locating of a fixture on the same wall as the others. After these manipulations, various evaluations are made according to the constraints already identified. Some constraints seem to act as tests; others such as "plumbing on one wall" direct the kinds of manipulations made. Even from these early and relatively simple transformations, necessary capabilities of an operable design system begin to emerge.

The second S has identified constraints for some opposite of 'cramped' storage, for more central space, for privacy for tub and toilet, and a desire for textured material. Texture, storage and privacy have been related to specific fixtures. His first operation on the existing design only removes the counter - assumed to be a response for more space (Fig. IV1). Then reacting to the constraint for privacy, he suggests enclosures for toilet and tub (Fig. IV2). After locating the enclosure, he generates an alternative for the last fixture by trying two locations; he uses the one responding to the constraint that storage be by the toilet (Fig. IV 3-4). Accessability to the toilet in this solution is poor and he thus reverses its location (Fig. IV5). This new location seems to be arbitrary; location on the right wall should have been equally acceptable.

Because no other means of providing privacy was considered (such as lighting) it must be assumed that an enclosure is a response directly emanating from this constraint. Because accessability to the toilet has played a role it must be included in the problem, either as part of the S's internal representation of the fixture or as an implicit constraint used to check the acceptability of a solution. In other words, some representation must allow for the S's recognition of this issue.

After generating an alternative acceptable to the existing constraints, the S recognizes a new one, that 'fixtures needing storage should be together'. Possibly, the coincidence of storage needs and privacy constraints encourages such a grouping of the fixtures. He brings tub and toilet together and encloses them (Figs. IV 5-6). Various other constraints are ignored in the search to fulfill this new one.

In both protocols, the first transformations of the problem are attempts to fulfill some of the initially identified constraints by manipulating various fixtures in a plan view. After the transformations fulfill the initial constraints, new constraints are applied. Some process evidently determines the sequence in which constraints are considered for resolution. The constraints identified and applied thus far by the Ss in either an internal representation or an external plan representation are: orientation of the toilet (possibly based on criteria concerning small areas separated from the major one), some reverse of 'cramped space', plumbing on one wall, accessability, privacy, and contiguity of fixtures. The manipulation of fixtures to fulfill these constraints has included: rotation of a fixture at a corner, the removal and relocation of fixtures, movement of a fixture along a wall, and the creation of an enclosure. While there has been trial and error activity in choosing manipulations, processes sometimes quickly allowed the Ss to find the appropriate manipulation for a particular situation. Each manipulation also requires the selection of the appropriate fixture or fixtures on which to act.

The discriminatory capabilities described above have been expressed in the two portions of protocols presented thus far. They, when combined with those found in other portions of the protocols, will provide a list of capabilities to be incorporated into a beginning model of design to be developed later.

New portions of the protocols follow.

PROTOCOL ONE: MIDDLE

PA 10: "I also feel that this tub position, along the wall, I feel very strange about it. I think the idea of orienting the toilet toward the middle of the room instead of the corner, is going to be a good one. There's something about hiding the toilet back here that I don't like.... There's the privacy angle, but there is also the puritanical thing, about the euphemism...It's something you pretend you don't have....Well, it makes me a little uneasy. The word bathroom is a euphemism....

PA 11: ....how much would it cost to run plumbing to both walls? (Exp: the cost would be 50¢ a linear foot.) I see why I don't like the tub over here. Having the tub with two corners exposed means you have problems with the shower arrangement. It requires an additional wall, or a curved shower rod. Let's see, is there anything wrong with a curved shower rod? I feel that there is....

PA 12: This method, seeing what I didn't like about the original arrangement, then eliminate what I didn't like. I've already done that. I have a large amount of space in here. Without cutting down on the functions. There are things I don't like about the arrangement yet. I have gotten more central space but some functions are cramped. I would like to see if I could iron those out without starting to chop up the space again. I suspect that this lack of space was the basis of the objection that it was not luxurious. I don't like the two sinks I have here. So close together.....

PA 13: (Draws Fig. VII(1).) Go back to the bath in the corner. Okay, wall at the end of it. Except that's too close to the (original?).....

PA 14: (Draws Figure VII(2).) I've put the tub along the same wall, but towards the window. It might allow you to put (Draws Figure VII(3-4), ...I was thinking the toilet could then go on this wall, leaving room for a large vanity along here. Which would work but cut down on the privacy....more than somewhat.

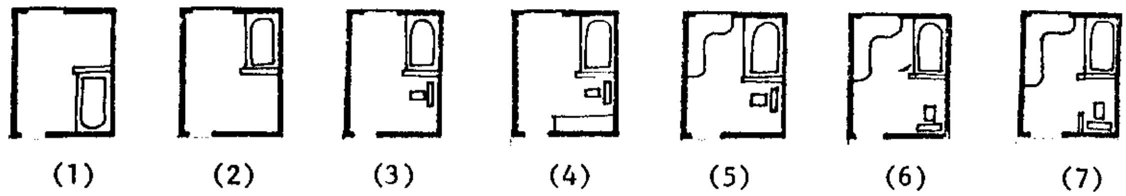


FIGURE VII

PA 15: (Erases and draws Fig. VII(5). This arrangement, with the tub in this corner, is the nicest space so far. It's open. I think it solves all the problems, except for this thing of privacy. It has a large space to stand around in to dry. It gives the appearance of space when you walk in. It's adequate; but not cavernous. It gives easy access to all the facilities, to the tub and to the toilet, and washbowls.

PA 16: I have an uneasy hesitation about the privacy. I feel as if that's a little of a two edged sword. We want privacy....This is my personal feeling. And I don't want to appear to try and hide the toilet. I have an idea that the client would like the toilet to be hid. I would like to make a compromise.

PA 17: (Adds to drawing as in Fig. VII(6).) It would appear as if you could do this. I don't quite know how. (Adds walls in Fig. VII(7).) There is this wall, by the toilet. It only comes out 2', which does not hide the toilet.

PA 18: This would be a good thing.....This does form a bit of a nook, but it isn't hidden from the door. This semi-enclosure for the toilet, plus this thing about the open plan. I think we're in good shape....."

PROTOCOL TWO: MIDDLE

PB 11: (Erases and draws Fig. VIII(1).) "5 ft. shower (Add to drawing as in Fig. VIII(2).).... we're stuck with this side view of the toilet. With storage space also just can't be along this wall. (Draws storage as in Fig. VIII(3).) Could only be a small cabinet....Could put it all the way up.... still a certain visual annoyance in not being able to see the window....

PB 12: I'd like to provide storage near the toilet, near the tub, and storage near the vanity area. It would be nice to fit the vanity into the storage area. I still want to maintain some dressing space around the tub.

PB 13: I'm trying to visualize this....For privacy for the toilet, there's the possibility of using sliding panels...perhaps to the ceiling, and if it were near the window, and were transluscent panels transmitting light, you'd get an interesting form against the panel, for anyone using the bathroom at the same time. [Laugh.]

PB 14: Sliding panels. I don't know how much cost this would add.... (Exp.: they run about $1.25 a sq. ft. installed.) So, if we are going to consider them, we might just consider 4 ft. room is 8 ft. tall? That's $50 right there. So using sliding glass panels can almost be eliminated. This is a difficult situation......

PB 15: The only way I could improve the toilet situation without a glass panel would be by varying the size of a wall. Now I suppose that would be less expensive than....glass.....

PB 16: This window area is not usable. For a sink, because of the inability to use a mirror. It's only OK for cabinet storage, or wall storage, which means that if it were used, it shouldn't be used for storage alone....this area is not usable for bath. It has water problems. Now it could be used....we need towel drying...that is certainly a possibility here.....

PB 17: Position of this door...makes it very difficult to use this wall, for storage. We don't want to move the door, do we? (Exp: (No.)

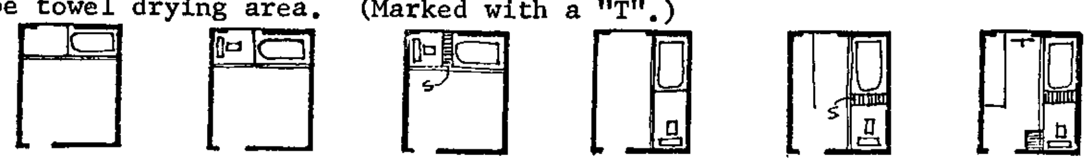
PB 18: .....we've thrown our plumbing system off now, thinking of storage in this area here...thrown in an extra partition. We need one here. We've also moved the plumbing system, which makes me reluctant to use that particular scheme.

PB 19: Draws Fig. VI(4).) Now if we were to do something like this and just reverse the position of the w.c....is there a standard amount of space that's desirable for using the w.c....I suspect that the 2.5' we have here is excessive. So it seems that 18" would be sufficient...or 2'. Actually we have 3.5 ft. to the seat. Might be able to get a small cabinet in this position......(Adds to drawings in Fig. VI(5).).

PB 20: One thing I'm trying to do is....the bath and w.c. I'm trying to not make in the same relative space. You'd have a storage unit here, w.c....

PB 21: ..now how much additional cost is involved when you can't run the plumbing up in a common.... or is this not true. (Exp.: We usually estimate 50¢ a linear foot for movement.) We're just adding 50¢ per linear foot? Add $3 additional cost. (Draws Fig. VI(6).).

PB 22: One thing this would do, if I could make that change. It would allow me a storage unit here, which would provide privacy for the toilet. But you still need the sliding door. There could be storage access from the toilet, directly into this unit, full room height storage. This could be towel drying area. (Marked with a "T".)



(1) (2) (3) (4) (5) (6)

FIGURE VIII

PB 23: This is a possibility. It gives me extra storage here. I'm not sure that I like this cut-up kind of feeling that I get from this. I have room for sinks and an extra vanity, too. One of my early considerations was temperature, and I had thought at that time of the possibility of sealing off the bath and the toilet areas, which are those areas that require a hard surface for cleaning purposes. Perhaps I could use some soft textured surface, even carpeting, for this....

PB 24: However, we're into trouble here because of the cost of sealing those off, of waterproof panels for an effective seal, unless we can think of something other than glass.....suppose plastic panels instead of glass. What is the cost? (Exp: It would have to be plexiglass so that it would not be breakable. It would cost the same.)"

Both Ss continue their search by first identifying,then applying more constraints to the problem. The first S seems to become involved in an attempt to resolve contradictions in his understanding of the relationship between toilet and privacy - to formulate a single constraint that reflects the complex information related to these concepts held in his memory (PA 10). Next, he retrieves a constraint prohibiting exposed corners of bathtubs (PA 11), then runs a check on the constraints thus far identified by re-applying them to the problem (PA 12). His search continues by moving the tub to a couple of locations, the moves again being represented in a plan view. The first location is disregarded. Possibly the S recognizes it as the original one for the bathtub, one that has already been tried (PA 13). A wall is located at the end of the tub to remove an exposed corner. Like the partition, which was a response to privacy in the Second Protocol, this S uses the wall at the end of the tub as a direct response to the constraint identified. In that this renewed search again begins with rotating the bathtub (see PA 9), it suggests that this S might possess a search priority that begins with bathtubs, the largest fixture.

He moves the tub, then locates the w.c., then the counter. The situation is evaluated and found to lack privacy (PA 14). The counter is moved to a vacant space. Another evaluation is made, again with privacy lacking (PA 15). In response, first the w.c. is moved, then a partition added (PA 18). Privacy in this case has evoked the generation of an enclosure, just as happened earlier in Protocol Number Two.

A variety of counter designs have been generated thus far. Linear, triangular, and "L"-shaped counters have been produced by S Number One alone. His concept and representation of a counter seems prototypical; he produces different counters for each context. A mechanism for producing counter representations in plan view would yield a linear entity that aligns itself along the edges of other entities, usually walls. (But not always; notice this S's second complete scheme, Fig. III 4 .) It can extend around corners, though possibly only inside ones. Inside corners and exposed outside corners of the counter are rounded. These generation rules are sufficient for generating representations of counters in plan view and may closely resemble those used by the Ss.

The second S continues his earlier design, altering it first by rotating the watercloset (assumed to be caused by inadequate room available for its use) (PB 11). He then adds a storage area between the tub and toilet. This relationship seems to form a pattern that is considered a step towards solution because he utilizes the relationsip several different times. This is not the only group of entities utilized. He also groups the tub, toilet and enclosure. He later attempts to utilize both groupings again, manipulating them as single units.

Each grouping thus utilized possesses the qualities of satisfying well a set of constraints. The constraints are evidently all those that have been identified among the fixtures involved and deal primarily with spatial contiguity. Thus, if manipulations are carried out while holding intact the set of satisfactorily resolved constraints, a new unit of manipulation will be produced. (Similar arrangements were also utilized by S Number Three.)

After reviewing the constraints thus far identified, S Number Two recognizes a new one. To gain light from the window, enclosures separating it from other parts of the room should be transluscent. After assuming transluscent partitions in his solution he recognizes the conflict that they produce with the constraint concerning privacy (PB 13). These attributes of the enclosure materials again seem to be almost "automatic" responses to the constraints. As no obvious means exists for representing opaque or transluscent qualities of materials in his drawings, it is assumed that the conflict is recognized only in the S's internal representation of the problem. The enclosure is abandoned when its interaction with the cost constraint is identified (PB 14). When the grouping fails because of other constraints (it turns out neither tub or w.c. can be in front of window), the S resorts to a fairly exhaustive search concerning the utilization of the wall area in front of the window. He searches all configurations to find those not possessing constraints that relate to it (PB 16). This particular search technique has not been expressed previously; all other sequences relate a technique consisting of fitting the necessary fixtures into a room sequentially until one set of locations meets all the constraints. The approach expressed in Protocol Number Two attempts sequentially to locate every fixture in a single location. Such a search approach has benefits only when the possibilities are extremely limited.*

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* As this S is an urban planner, it would be interesting to find out if his search procedure here is more common to his profession than to the other design professions tested. His is the only expression of this approach.

After considering the left wall in a similar type of analysis (PB 17), the S moves his grouped unit to a new location to see if its satisfactory resolution of a set of constraints can be utilized in an alternative location (PB 18). Just before relocating this "grouping" he recognizes for the first time a constraint for a single plumbing wall. Upon inquiring he determines that the sensitivity of this constraint in fulfilling the budget goal is relatively low (PB 21). This is a rare example where a S has evaluated the sensitivity of a design constraint for achieving a design goal. This point is taken up again later.

Learning that 'plumbing on one wall' is a relatively insensitive function of cost, the S reviews the constraints identified to date (PB22-23). He recalls the desire for textured materials in the form of carpeting and recognizes that its inclusion is dependent on a tub enclosure (PB 23). On retrieving information suggesting that partition cost would vary according to materials, he ends this portion of the protocol with a search for alternative materials to glass. Glass can be assumed the first priority material for bath enclosures, plastic the second, in this S's association processes (PB 24).

Unique mechanisms identified in these protocol excerpts can be listed. A new manipulation located fixtures (in a new design iteration) in a corner or next to an existing fixture. Additional constraints identified included: no exposed tub corner, no direct view from door to toilet, light from window to most parts of the room, locate mirror where it is to be used, and bathtub not located by window.

Let us now look at the last portion of these protocols.

PROTOCOL ONE: END PORTION

PA 19: ".....There's another possibility of putting sort of a console coming out from this wall. (Draws Fig. IX(1).)....mirror in here... probably a large sink in here and a smaller one here. This would have nice accessability. I'm not terribly enamoured with the design..... I feel myself sort of getting into a corner. (Draws Fig. IX (2-3).).... This again leaves the toilet...in the open.

PA 20: Come to think of it, I wonder if the original design with.... (sketches Fig. IX(4).) Now this seems to be a nice arrangement here. You get these facilities in a small amount of space. But that leaves the toilet here, which is sort of exposed some to think of it.

PA 21: I wonder if the original design, replacing that console........ (Draws Fig. IX(5).) I was thinking of bringing the vanity underneath the window, into this area. But that would leave...sort of a nook.... by the toilet.

PA 22: (Draws Fig. X(6).) This one would do it. This one is getting familiar....It would be nice to have an arrangement like this because it gives some privacy to the toilet, the bathtub still has lots of open space. Unfortunately that means putting...if you're going to have the toilet here means you have the washbowls over here, I think to get the people's backs to the toilet......this will work out nicely.....Yeh. That's just fine.

PA 23: My objection here was that....I dislike rounded corners on these things. It reminds me of artists' palettes. But it also keeps you from scraping your thighs...I think what I've got right here....it's simply a matter of juggling proportions.

PA 24: I'd sort of like to have this washbowl right in front of the window. Just have this nice and neat for its length down to here. The length of the counter so it lines up with that wall. Bring the sink down as far as I can so...I think a little space here for shaving cream and stuff like that...make a little more space so you can get two people using washbowls at the same time without being right up against each other...... This mirror down to there. There's still some details...(Draws Fig. X.)

PA 25: Right now the biggest objection I have is that the mirror, I think visually, and functionally would be quite nice to have a large mirror here. Of course, not with the window or wrapping around the corner. I think the

(1) (2) (3) (4) (5) (6)

FIGURE IX

large mirror seems to conflict with having the medicine cabinet....That window doesn't come to the edge either....Well, let's put the medicine cabinet mirror in front of this sink. And then optionally you could extend this mirror anyplace along this wall. To carry through visually.. ...If it were easier to get a mirror in standard size that doesn't match the window, well, that's the way it goes...Yes. Here's a place for the towel rack. I'd forgotten about that. Pretty essential to have a place for towels. Near the bathtub, also along here would probably make sense. Towels in this area. They'd be accessible from both the bathtub and the sinks....I think that's it."

PROTOCOL TWO: END PORTION

PB 25: "One other possibility, using this window area for the toilet which is solving...Oh, I remember why I did not consider this. In order to get privacy in this position we need to screen the area and you can't do that without a transluscent material (No representation. Assumed to be as in Fig. XI(1).)

PB 26: I think that I would...like to get a better relationship...... with the emphasis on storage...we're creating problems if we don't try to use the walls and partitions we have, or similar walls. What is the cost of a partition? per sq. ft.? (50¢ a linear foot.) Not very expensive....I'm really hanging myself with this particular area here, where

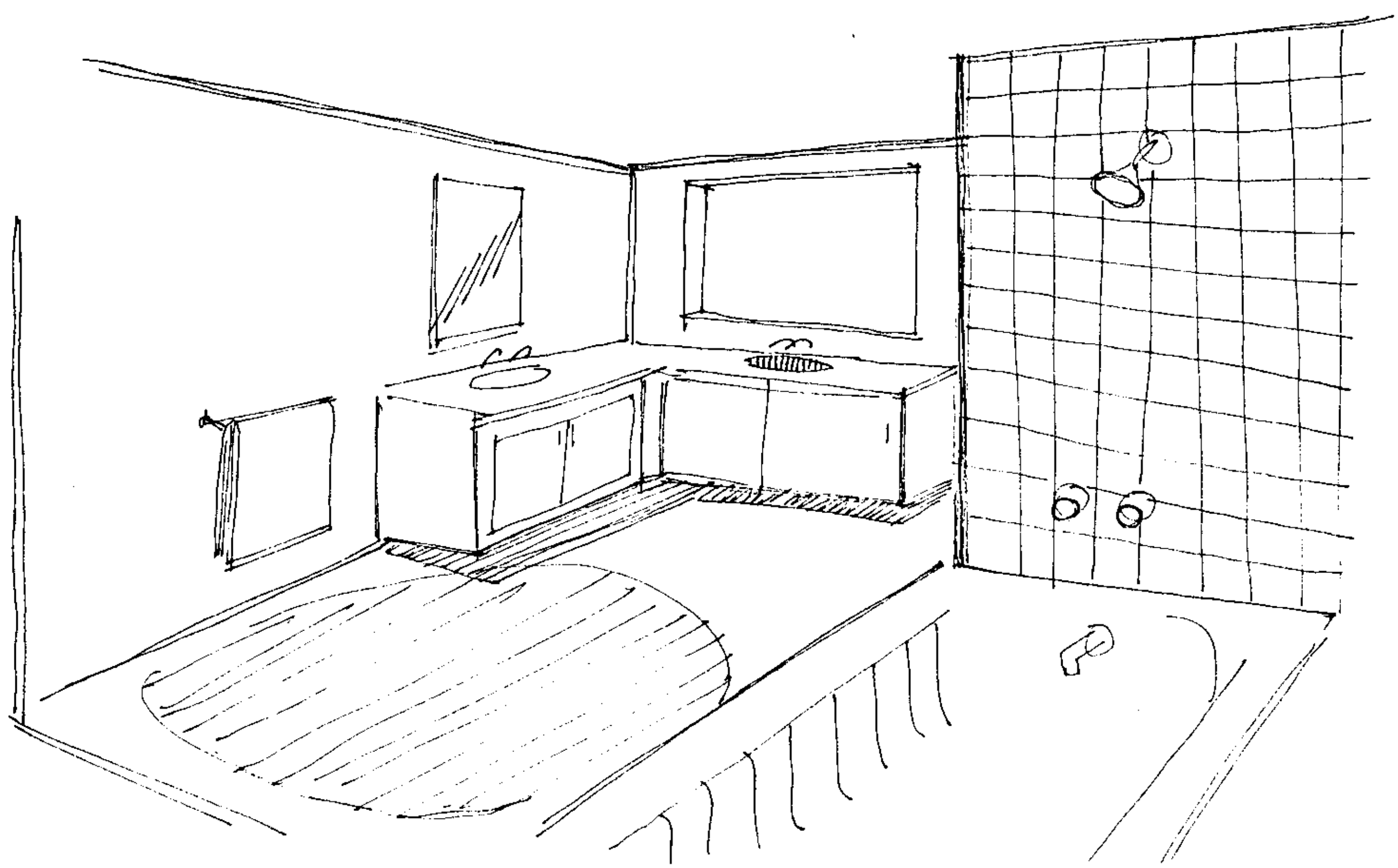


FIGURE X: PERSPECTIVE DRAWN BY S ONE

the tub and the toilet area...The problems of privacy and covering up this window, obviously, the door entrance here....

PB 27: (Draws Fig. XI(2).) If I were to turn the tub and utilize this wall, I have a problem again, having to put a partition in here. This could be done. You would have to leave this area open, the area for drying off, dressing for the tub.

PB 28: The toilet still has to be in this area because of the window. (Draws Fig. VIII(3).) I could do something like this...tub would be against this wall.....

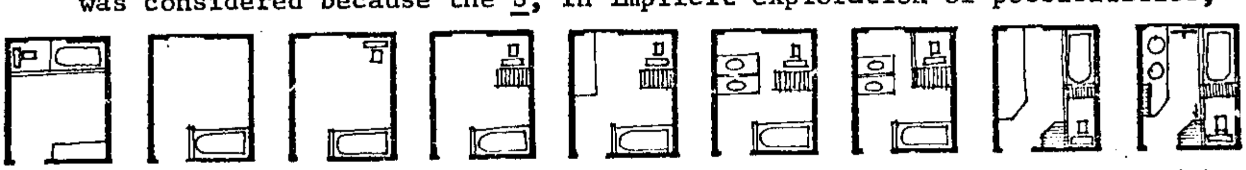
PB 29: storage between would really help us to a great extent. (Draws Figs. (4-7).).... Any time we try to have the sinks back to back....

PB 30: No point in blocking off the only window and the natural light. We still have the problem of not getting the extra storage in....

PB 31: (Goes back to an earlier plan and changes it as in Fig. XI(8).). Make this thing turn here....In this scheme, we're allowing the storage to provide some of the privacy for the toilet...We have our bath and washing area, adjacent....allow this [storage] to be ceiling high. Virtually lose this space which is undesirable....Actually this is just a reverse of what we had before....

PB 32: (Adds to Fig. as in XI(9).). This can become a storage cabinet. Now, one thing that can be done here...This, within the cost constraint, we could include a sliding door here. Anytime access to storage was desired, this door would probably be closed. If it wasn't it would go right back into this position. Storage cabinet to the ceiling here. Towels, here, the sinks themselves could and the countertop could begin under the windowsill. This could continue...same position...here. Adequate access...This way we provide sinks with an extra countertop. Perhaps a whole mirror here. Let's check the cost again. $3 extra plumbing. This would be towel area. Leave just this much mirror. Even make that much storage cabinet. The mirror comes right up to here. Storage here...Okay, that's about all."

The First Protocol continues by considering a new alternative for the form and location of the counter (PA 19). It is assumed that this arrangement was considered because the S, in implicit exploration of possibilities,



(1) (implicit) (2) (3) (4) (5) (6) (7) (8) (9)

FIGURE XI

generated it and perceived that it fulfilled most of his constraints. It was abandoned when its liabilities became apparent (or its similarities to previously explored arrangements). He returns to the original arrangement of bathtub and toilet as an appropriate arrangement for the right wall and searches for a location for the counter (PA 20-21).

He is able to return to this earlier arrangement because he has access to previous solutions. (They were right in front of him, represented in a stack of earlier sketches.) The S's constraint testing operations are not limited to the current state of the design problem, but can also be applied to earlier states. In this way, paper and pencil are utilized as an external memory.

The S quickly moves toward a final solution. For access to the toilet, the counter is cut back as shown in Fig. IX(5). It is carried around the corner to gain the needed counter area and add distance between toilet and washbowls. Corners are rounded. The S finds that all the constraints he has identified are resolved by this arrangement. Detailed relationships are then considered. One washbowl is centered in front of the window. The edge of the counter is aligned with the end of the bathtub on the other side of the room. The S ends by drawing a perspective. See Fig. X. In it, the horizontal lines between mirror and window are aligned. Last, towel racks are located near the sinks and bathtub. (These items have not been mentioned previously.)

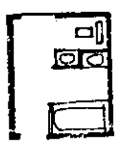
The last operations primarily responding to aesthetic constraints, have not been applied earlier. Quite obviously they represent constraints that can be fulfilled with almost any arrangement; alignment and centering would be possible operations on any configuration. It seems this S utilizes two priorities of constraints, major constraints used in finding a general solution, and detailed ones for refining it, once it has been found. It is likely that in more complex problems, more sets of constraints of different priority come into play during different phases of design.

The last portion of the Second Protocol begins with the expression of an alternative configuration for which no external representation is ever made (PB 25). It is internally created by manipulations, constraints are applied against it and it is rejected, all within the S's head. It is assumed that the configuration being considered is that presented in Figure XI(1).

He makes one other exploration beginning with the bathtub in a new location. Because of the area restricted by the window and door, he. locates the watercloset in one location. He then recognizes that his old relationship, with storage between toilet and bathtub, is appropriate here (PB 27, 28, 29). After this manipulation he tries two sink locations, one along the wall, another back to back (PB 29). (The earlier rules for generating counter designs would have difficulty producing this back-to-back configuration.) The second location is rejected becuase it blocks the window; possibly the constraint concerning spaciousness was also an implicit cause (PB 30). The reason the first sink location is rejected is never given.

After trying these possibilites and recognizing that his time is running out, the S reviews his earlier alternatives and begins working on the one that had earlier been considered "a possibility" (PB 31). (The protocol offers only sparce documentation here.) He seems to recognize the difficulty of putting in a swinging door to the watercloset and proposes a sliding one (PB 32). He rightly perceives that when a person may want to get into storage from the inside of the toilet room, the sliding door would be in a closed position. He does not realize, though, that anyone getting into the storage from outside would be able to see into the toilet room. Minor alignments are made and he is finished. Figure XI(9) represents his final solution.

These two Ss, along with the other two, are able to produce a solution by the end of the allotted time. At a point shortly before the time limit, each S discontinued his exploratory manipulations of the problem and reviewed the alternative schemes he had thus far developed. Taking the most promising of these, that is the one which fulfilled the greatest number of identified, relevant constraints, he began a refinement. The refinement included an attempt to fulfill each of the as yet unfulfilled constraints. All Ss



Solution - Subject Four

Solution - Subject Three
(Tracings of his sketches)

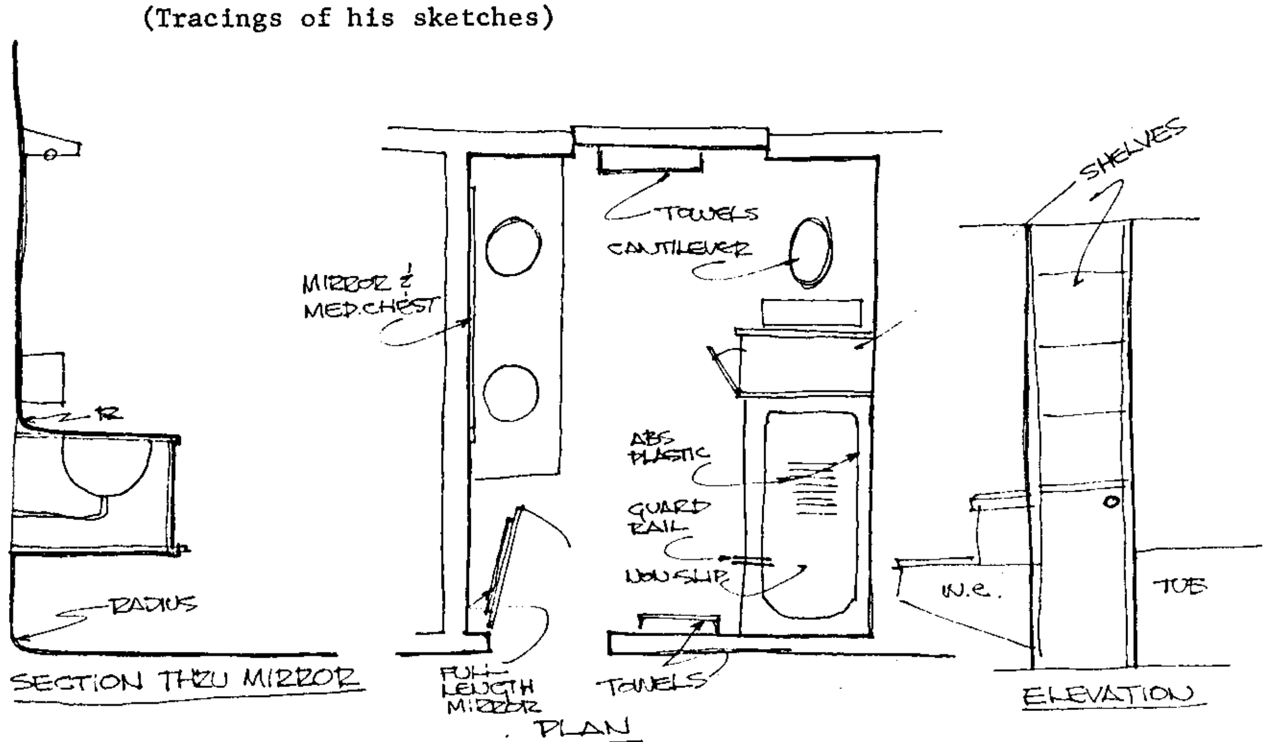


FIGURE XII

essentially ended the problem by not generating any more constraints and by attempting to fulfill those already identified with the configuration that best responded to them. (In all cases, a configuration had been generated that came close to ideally fulfilling all constraints. In a situation where this is not the case, more complex processes probably transpire.) Three of the Ss applied new detail constraints such as visual alignment at the end of their process. The solutions of the other two Ss are shown in Figure XII.

SUMMARY

From the identification of constraints used to evaluate alternative configurations, the manipulations made, and the entities acted upon, the total information that has been utilized in this design problem can be listed. See Figure XIII. This information is assumed to represent a large portion of the input (stimuli) that determined the S's responses. Some information used may not be listed. Throughout the protocols evidence was gained that internal processing was taking place. (For example, in the end excerpt of Protocol Two, PB 25.) In all cases, only information expressed or necessary to make the expressed operations has been included in this Figure.

Besides the information listed, each S also used a set of rules, that is, conventions, for representing fixtures in plan view and other forms of graphic representations. These conventions have not been presented here, as they can be found in almost any text on architectural drafting. (For an instance, see Bellis and Schmidt, 1961).

Besides identifying the information utilized in the problem, the analysis has also suggested some of the ways in which this information was

FIGURE XIII (PART A): Constraints, Design Units and Manipulations Made in the Four Protocols. The S utilizing each is shown along with the representation in which it was utilized. (They have been described in their most general form.)

Constraints:

C1. main area of room has a minimum clear area (1,2,4)(PLAN)

C2. sink in separate visual field from watercloset (1,2,3,4)(PLAN)

C3. fifty dollar budget (1,2,3,4)(VERBAL)

C4. mirror located at place of use (1,2,3,4)(PLAN)

C5. easy access and use of fixtures (1,2,3,4)(PLAN)

C6. easily maintained materials (2,3,4)(VERBAL)

C7. plumbing fixtures on one wall (1,2)(PLAN)

C8. no view between watercloset and door (1,2,3)(PLAN and PERSPECTIVE)

C9. well lit room (3,4)(PLAN)

C10. visually separate sink and bath (2)(PLAN)

C11. medicine cabinet behind mirror (1,)(VERBAL)

C12. include textured materials (2)(VERBAL)

C13. no barriers between window and rest of room (2)(PERSPECTIVE)

C14. areas required storage should be together (2)(PLAN)

C15. use cantilevered watercloset (3)(SECTION)

C16. use non-slip material for bathtub bottom (3)(VERBAL)

C17. include lockable storage (3)(VERBAL)

C18. distance between floor and faucets < 27" (3)(SECTION)

C19. distance between floor and faucets > 30" (3)(SECTION)

C20. no bath in front of window (1,2,3)(PLAN)

C21. upward light at counter (3)(SECTION)

C22. stability of stool (3)(VERBAL)

C23. storage for stool (3)(SECTION)

C24. flushmounted fixtures (3)(SECTION)

C25. mixing head faucet (3)(VERBAL)

C26. hand support around bathtub (3)(SECTION PLAN)

C27. no exposed bathtub corners (1)(PLAN)

C28. unused space should have 2 sides adjacent to main space (1)(PLAN)

C29. watercloset oriented towards center of room (1)(PLAN)

C30. edges should align (1,2)(PLAN and PERSPECTIVE)

C31. easy movement between fixtures (4)(PLAN)

C32. luxurious materials (4)(VERBAL)

C33. towel racks near sink and bath (1)(PLAN and PERSPECTIVE)

FIGURE XIII (PART B): Constraints, Design Units and Manipulations Made in the Four Protocols.

Design Units Acted On:

DU1. Bathtub (1,2,3)(PLAN)

DU2. Watercloset (1,2,3,4)(PLAN and SECTION)

DU3. Counter (1,2,3,4)(PLAN, SECTION and PERSPECTIVE)

DU4. Sinks (1,2,3,4)(PLAN)

DU5. Mirror (1,2,3,4)(PLAN and PERSPECTIVE)

DU6. Towel racks (1,2,3)(PLAN and PERSPECTIVE)

DU7. Enclosures (2,4)(PLAN)

DU8. Enclosure materials (2,4) (VERBAL and PERSPECTIVE)

DU9. Storage (2,3)(PLAN, PERSPECTIVE and SECTION)

DU10. Window (3)(PERSPECTIVE)

DU11. Counter design (3)(SECTION)

DU12. Medicine Cabinet (1,2,3,4)(PLAN, SECTION)

DU13. Bathtub design (4)(PLAN)

DU14. Watercloset design (3)(PLAN and SECTION)

DU15. Wall materials (3,4)(VERBAL)

DU16. Floor materials (2)(VERBAL)

DU17. Counter materials (3,4)(VERBAL)

DU18. Bathtub bottom (3)(VERBAL)

DU19. Window pane material (3)(VERBAL)

DU20. Light fixtures (3,4)(PLAN and SECTION)

DU21. Counter height (3)(SECTION)

DU22. Stool (3)(SECTION)

DU23. Supports at bathtub (3) (SECTION)

DU24. Bathtub faucets (3)(SECTION)

Manipulations:

M1. Locate Unit at a corner (of a fixture or room)(PLAN)

M2. Rotate Unit at present location (1,2,4)(PLAN)

M3. Move Unit to another corner on some wall (1,2,4)(PLAN)

M4. Move Unit to corner on another wall (1,2,3,4)(PLAN)

M5. Choose Unit or its attributes (2,3,4)(SECTION AND VERBAL)

M6. Enclose Unit (2,4)(PLAN)

M7. Reverse location of Units along wall (1)(PLAN)

M8. Locate wall next to Unit (1,2,4)(PLAN)

M9. Return to earlier solution (1,2)(PLAN)

M10. Align (1,2)(PLAN and PERSPECTIVE)

M11. Locate over sink (1,2,3)(PLAN)

structured and how the transformations were organized. The sequence of operations carried out by the Ss in all protocols followed a general organization of first transforming the current state of the design into a new one in order to better fulfill certain constraints, then evaluating the new state of the problem in terms of the constraints previously identified. The constraints not fulfilled sometimes gave direction to the kinds of transformations that should next be made. Quite obviously, then, the S had direct access to a list of identified constraints - some portion of the information given in Figure XIII. It is also clear that the general format of their activities is similar to what Newell and Simon call "generate and test." (1967 p. 248-253). The Manipulators generate new problem states which are tested by the constraints.*

Some generate and test sequences seemed to involve an undirected trial and error approach for applying transformations to resolve constraints; a large number of different alternatives were tried until an acceptable one was found. This was particularly true when a great many constraints were being considered simultaneously. At such times it seemed that simple priorities of operators were the guiding mechanisms. At other times the search was quite directed. When the attributes of materials were selected no trial and error mechanism was evident. The constraints directly designated a particular attribute. Specific Ss resolved certain spatial constraints by associating the constraints to a particular transformation. The creation

*Newell and Simon also posit the existence of a response process that acts after the operators designated Generate and Test, ending mediation. From this study no clear distinction could be drawn between mediation, e.g., mental processing, and behavior in complex situations. Generation of a state may take place internally or externally. The difference in activity between a mental association between concepts and between a concept and a motor control seem indistinguishable - at least in design problem solving activities.

of an enclosure as a response to the constraint for privacy was one example. Other constraints directed transformations not by an association to some specific manipulation, but by encouraging a variety of manipulations in a limited spatial realm. 'Plumbing on one wall' was one example; the mutual use of a fixture and storage suggesting they be in proximity, was another.

Added to these means for relating information was the ability to utilize grouped configurations resolving some subset of the constraints in the transformations of the total design. This occurred when fixtures were redesigned (by subject Number Three) and when a group of fixtures were manipulated as single units (Subject Two, PB 18-19). This hierarchical organization allowing components to be designed as part of a whole is an important capability of designers. It was also found that designers were able to return to earlier problem states. Three of the Ss also applied a new set of constraints in finishing their solution. These included the visual alignment of edges and the location of towel racks. It is implied that theypossessed at least two priorities of constraints and applied one set after the other had been fulfilled.

These means for structuring processing mechanisms outline the beginning of a general specification for an operable model of cognitive design processes.

PART THREE

AN OPERATIONAL DESCRIPTION OF DESIGN PROCESSES

From examination of the protocols gained in the experiment, further insights into the original hypotheses are now possible.

DESIGN UNITS

An hypothesis of the original report concerned the structure of information used in design problem solving. That structure was suggested as being a significant influence on the organization of the problem solving process and in retrieving relevant design information. The hypothesis stated that physical configurations were the central units of that structure.

The _S_s in this experiment all began designing by generating for themselves a working formulation of the problem; these efforts continued throughout most of the process. A working formulation consisted of the identification of a set of unfulfilled constraints that seemed to respond to the problem goals and a set of configurations making up any solution. To tell whether constraints were fulfilled, the _S_s had to determine when and how they applied; they had to determine to which physical configuration they were relevant.

Most physical configurations in this experiment were identified from the existing solution. Some _S_s also considered others that were retrieved from memory.* Storage was the common configurational unit retrieved from memory. Some constraints and their configurations seemed to have been

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* This particular problem consisting of a re-design does not emphasize Design Unit identification.

simultaneously retrieved. The examples from Protocol Number Three of a mixing head faucet, recessed fixtures, and hand rail suggest that a constraint and its solution are sometimes intimately bound together.* Most often though, the sequence of retrieval was a configuration, then the constraints relevant to it.

Once a configuration and its constraints were identified, the Ss made transformations on the problem, configuration by configuration. In this respect their activities corresponded well to the hypothesis concerning the use of Design Units. All Ss used the sequential placement of fixtures to generate spatial organizations. In Protocol Number Two, the S at one point chose to try all DUs in a particular location (in front of the window). Recognizing that the window is a DU, this case also can be interpreted as the search for how one DU can relate to others.

Examples within the protocols did show cases where a constraint was identified first, then a range of configurations sequentially retrieved and searched for the one best resolving the constraint. Alternative means for a variable counter height in Protocol Number Three was one example. The expression of a desire for privacy in Protocol Number Two was another (PB 4). Yet these cases were relatively rare. Linguistic habits affect any verbal report, making exact comparisons of the frequency of different sequences of retrieval difficult. But considering only those cases where the sequence of retrieval was unambiguous, 86 percent of the constraints identified in the four protocols were retrieved after the fixture for which they were relevant. The other fourteen percent were identified constraint first.

* In that the S had been told to think about the problem prior to the experiment, simultaneous retrieval may be the result of associations made earlier.

Thus these protocols suggest three points:

(1) All Ss transformed problem information into a solution state primarily by operating on information about one physical entity at a time. The transformation sequence was ordered by these entities.

(2) Only information associated with an entity was utilized in solving the problem. Little evidence was given that designers generate a constraint, then search for various entities that may optimally fulfill it. Rather, the protocols showed that the predominant influence of a constraint in design is towards refinement of the general form of an already identified entity.

(3) The concepts defining classes of configurations for a solution were directly assumed from the problem class itself and from the problem situation. Little exploration was made of alternative classes of configurations that may have effectively responded to the problem.

A variety of psychological experiments suggests the primacy of objects in man's memory structure. Recall tests have shown that a noun cue allows an easier adjective recall than the reverse sequence. This has been found true for both concrete and abstract associations and for associations of both high or low probabilities. (Lamber and Paivio, 1956; Gorman, 1961; Paivio, 1963; Kusyszyn and Paivio, 1966).* In free association, noun-noun relations are more common than any others. Moreover, other associations, such as adjective-adjective, have been experimentally interpreted as being retrievable only because they represent the conceptual intersection of some

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* Theoretical bases for these results are developed in Quine (1964) and Miller, Galenter, and Pibram (1960, p. 134-138).

already recognized (though implicit) noun. (Deese, 1965, p. 142-152) Thus "soft" is associated with "furry" because of the large class of animals at their semantic intersection. Thus, physical objects - nouns - seem indeed to be the central concepts upon which man's information about the physical world is normally structured. This "natural" structuring encourages problem organization in design to take a similar structure by making certain associations easier than others. The structuring of information in this manner also seems to facilitate its application to design problems. Entities related to other entities are readily available for recall. Constraints are stored in a fashion allowing them to be easily linked to the configurations for which they are relevant.

If such an organization of memory is true, then retrieval from memory of the attributes relevant to design problems may be impossible without conceiving of physical entities first. Design Units, as entities, then seem to be a necessary component of most thoughts about a design problem.

The observed predominance of physical "things" in the conceptual organization of design problems is better understood when the predominance of this mode of classification is recognized in man's ontogenetic development. The work of Kuhlman, as related by Bruner, emphasizes that humans learn the organization of the world first by learning to perceptually classify its physical parts. (Bruner, Olver, et al, 1966, p. 26-29). Only during later ages do we generally gain a rigorous knowledge of attributes, functions, or hierarchical orderings. (Bruner, Olver, et al, 1966, Chapter 3). Thus, a task emphasizing perceptual and spatial cues would reasonably rely on those concepts first gained perceptually; that is, before learning becomes verbally oriented.

Some exceptions to the organization proposed were found. The second S identified privacy as a constraint for his design before he determined where the constraint was relevant (PB 4). In this case, it seems likely that privacy may have been associated with the general problem concept, that is with bathroom. Possibly, attributes related to general Design Units must be translated to more specific ones during design. This reasonably suggests that all the attributes related to "house", i.e., "warm, cozy, informal", would have to be related as constraints to specific physical aspects of a house to be fulfilled. The only unambiguous exception was given by Subject Number Three in recognizing the desirability of a variable height counter, then searching for physical means for accomplishing it. Deese argues that adjectives form strong associations with nouns only when the adjective is rare. (1965, p. 151-152) Possibly this is an example of such a case.

In essence, a structure of semantic and pragmatic information has been suggested for information concerning objects of the physical world. Its outline seems similar to a subset of the memory structure being developed by such linguistic theorists as Quillian (1966) and psycholinguists as Deese. The structure consists of information elements connected by linkages. The major elements are Design Units, strongly connected to certain others. A DU is also strongly linked to its constraints. Only weak links, if any at all, relate constraints with a variety of DUs. The implication is that strong associations are not reversible. The structure is ultimately connected; all elements can be reached from any other element.

From such a structure specific instances of a class of configurations seem able to be generated, either by recalling specific total configurations of some past "experience" or by decomposing a DU into its component Units and generating specific configurations for the components, then recombining them into a possibly original example of the total Unit.

Two processes have been identified to search this structure. Both processes provide the necessary means for ending such a search. By searching memory for information both related to all bathrooms and related to the perceived information concerning the particular problem, a double pronged search is instigated. The search ends when the two "search trees" link together. The two methods expressed in the protocols emphasize one or the other prong. The protocols suggest that strategies may exist for sequentially carrying out such searches.

DUs are evidently an important, natural organizing component for design information. Based in man's linguistic and perceptual development, they act to strongly augment his design problem solving capabilities. Without such assumptions an undefined search realm exists for a designer that potentially includes all possible configurations of entities in all possible arrangments. The empirically derived assumptions about the form of the solution of a problem, as expressed in DUs, are powerful, and possibly necessary, for delimiting a reasonable solution realm. Because they are heuristic and involve unconscious conservative assumptions about the form of a solution, DUs are indeed also potential limitations to design creativity. (See Alexander, 1964, p. 66-70.)

PROBLEM IDENTIFICATION

The S's intermixing of information retrieval and processing was a major source of complexity and individual variation in the previously described processes. While it has been possible to make distinctions between information retrieval and processing in the analysis of the protocols, the two activities were, in actuality, intermixed. The inherent logic of simultaneously transforming and redefining problems is highly questionable. Transformation states evaluated within one problem definition may receive a different evaluation in another problem definition. The S's reliance on information gained from transformations made on only a partially defined problem makes their efforts truly subjective (and haphazard). Because of the inherent subjectivity of information retrieval, the following discussion and later operational analysis will treat separately each activity.

The task of defining a design problem is difficult, it seems, primarily because of the amount of information potentially relevant. It is primarily a search problem within a pragmatically and semantically stored memory. Two major approaches and one variation have been identified as means for problem definition. The first approach relied on given information to structure search in such a way as to point to various constraints that could be retrieved from memory. The other approach retrieved possible constraints directly, then attempted to relate them to the problem by finding how and where they may be applied. In Protocol Number Two, this approach was used to retrieve constraints randomly. Subject Number Three, on the other hand, retrieved them according to the fixture for which they were relevant. The two approaches search memory by relying on different aspects of its organization. The first technique's power lies in that it can be repeated after each proposed configuration is generated. That is, it allows for the elicitation of new comments from a client and can utilize any new information accidently introduced. The second technique utilizes no external aids. Though the retrieval procedures were elucidated by the S's expression of verbal materials, it is assumed that the same techniques are used to retrieve motor, tactual, visual and other types of stored information. Retrieval processes identified here are dependent upon the original encoding of subjective experiences. Thus problem identification is not deterministic. But given any already structured memory, these two strategies begin to suggest means for searching it. The two approaches described can be called "pure" retrieval strategies; no S used only one; often they were mixed together.

Because of the before-mentioned psychological influences, as expressed in the work of Paivio and others, concerning the associational strengths of linkages going from object to descriptor, the technique of retrieving constraints by DUs seems particularly powerful. Further study of human information retrieval techniques is needed; the relative productiveness of this and other techniques is a potentially fruitful area for research.

In each of the previous excerpts, a constraint is identified as relevant because it is assumed to represent a function of a more basic goal of the problem, in economic, aesthetic, functional, or other terms. The orientation of the toilet is assumed to significantly decrease wasted space in Protocol One; the addition of more storage is assumed to significantly add to the functioning or desirability of the bathroom in Protocol Two. Quick reflection shows that the relations between goals and constraints developed by these designers are highly subjective. Though they are applied as if they are relevant for all people, they are at best only probabilistic. If a constraint is utilized, it is also assumed to be a sensitive function (in the mathematical sense) of a goal, or at least that no more sensitive functions have been omitted. It was found that the intuitive designers tested seldom examined the significance of the information they retrieved, in either probabilistic or sensitivity terms.*

PROBLEM REPRESENTATION

In manipulating the fixtures to produce a configuration fulfilling all constraints, the first two Ss, and the last one, externally utilized a plan view representation. It was clear that internal manipulations were also occasionally made; some decisions came from constraints that could not easily be expressed in their external representations (i.e., the second S's discovery of the toilet silhouette against the window). The implication is that the S's internal representation is more general than a plan view.

Not all Ss worked externally on only a plan view representation. S Number Three also heavily utilized vertical section views. This S generated many constraints concerning the details of the bathroom fixtures and did not concern himself with the relationship between fixtures to the degree that other Ss did. This S was able to produce many constraints that could be represented in section only. Because the other Ss did not externally utilize sections, it may be assumed that they either did not readily possess the requisite rules for representing information in section or that they did not

*At this point the general similarity of all design problems is again evident. It is seen here that for ill-defined problems, intuitive designers develop algorithms describing the relationship of a constraint to a goal in an informal way. Engineering formulas used in formal analyses are the counterparts from those fields dealing with well-defined problems. Well-definedness then means that the relevant constraints and their relations have been formalized through empirical study.

have the information necessarily expressed by such representations. S Number One finished his solution by drawing a perspective, another means for representing the problem. The aspects of Protocol Number Two that suggest an internal representation other than plan are also easily incorporated into a perspective representation. The fourth S seemed to work, both internally and externally, in plan and perspective also.

Besides plan, section, and perspective representations, Ss also utilized verbal descriptions of fixtures and materials to qualify what was desired. Constraints for luxurious materials, a mixing head faucet, and textured materials also have no representation in a plan view. While some may be represented in perspectives, all may be represented most easily through verbalization. They seem to be verbal "tags" tied to the appropriate fixture concept. While sometimes listed on paper by the Ss, these "tags" were mainly held in their internal representation.*

Thus, at least four representations have been identified from these studies: plan, section, perspective, and verbal tags. Manipulations were identified that acted on each of these representations. See Figure XIII.

The transformations of DUs and constraints into the graphical representations used in these protocols is essentially what is taught in the instruction of drafting. Within these representations, manipulation rules are informal, because plans, sections, and perspectives are homomorphic in a limited way with the entity being designed. Essentially, each representation consists of a set of symbols that expresses certain kinds of attributes, compositions or relationships of DUs. From manipulations on the representations, new information may be inferred. Plans allow horizontal relationships

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* The two general types of representation identified here, verbal and visual-spatial, correlate well with some theories of the nature of intelligence. (See Smith, 1964; Guilford, 1967.)

to be expressed; vertical sections show information concerning vertical relationships and, because of gravity, information concerning structural support. Other information may also be available.

Besides determining the appropriate DU where a constraint could be applied, each S needed to identify the appropriate representation that could express the constraint. Since constraints were generated that were never externally represented (e.g., for cleanliness, by Subject Number Two), the transformation of an internally available constraint into an externally expressed one seems not to be trivial. It seemed necessary for Ss to have learned specific symbolic means for externally representing aspects of problems.

Each S chose some type of external representation for aspects of his problem and then proceeded to represent DUs in it. The representation, in requiring certain information to be expressed in the mere representation of some entity, determined the kinds of information that had to be determined about each of the Units. To represent a counter in plan view, its depth must be determined; a bathtub could not be located without also deciding on its shape. Because plans express well the horizontal relationships between fixtures, consideration of these was encouraged in this representation. The significant point is that each representation demands the determination of certain types of information while not expressing other types at all.

Thus, those external representations available and utilized by a S significantly influenced his solution in at least two ways. It offered a limited means to store and manipulate certain types of information with only a minimal load on memory. It also influenced the kinds of constraints likely to be retrieved by demanding determination of certain information so that it could be represented. The accumulated store of visual, motor, and tactile information in each S's memory allowed internal representations richer than any single external representation. Any model of a design problem solver must recognize both the internal and external representations of design problems.*

PROBLEM TRANSFORMATIONS

The means by which the Ss in the protocols were observed to retrieve information from both the problem statement and their own memory corresponds well with the initial hypothesis concerning Identify as an integral operation in design. It was found that Ss retrieve constraints and DUs both from memory and the problem statement, (possibly from other information storage units also). As this is being done, constraints and DUs are related together, determining where constraints are to be applied. Identification procedures continued throughout most of the process and were interjected between other activities.

The Identify operation also involved a choice of representation. Before a S could begin resolving constraints for or between DUs, he had to choose some means for representing them. His choice was determined in part by the representations and manipulations available to him, and the kind of information he wished to represent.

Once a set of constraints and DUs had been initially identified and means for their representation found, the design problem consisted of finding some configuration of the DUs that fulfilled the constraints. The means by

* A significant issue for design methodology should be the production of a representational means capable of efficiently treating the wide variety of information utilized in problem solving. (See Minsky, 1963, pp. 448; Ernst and Newell, 1965.)

which each S represented his problem at this stage determined the kinds of transformations that were available to operate on the information. The operational issue for each S, then, was to determine the appropriate sequence of operations, (which are here called Manipulations), that transformed the initial problem into a configuration fulfilling the identified constraints. The magnitude of his problem becomes evident when the range of Manipulations, DUs available for manipulation, and the constraints that any configuration must fulfill, are considered. As can be seen from the information listed in Figure XIII, the possibilities are large. A small amount of research into the problem by the Ss would likely have produced even more. Given the limited set that was generated in each of the protocols, each S must have had some means for sequentially administrating constraints, DUs, and Manipulations in an order that transformed the initial problem into a solution.

An original hypothesis suggested that two operations were available to act upon the information structure: Generate and Integrate. The experimental protocols allowed a level of analysis offering major refinement of these very general descriptions. The following discussion abandons them as a basis for significant analysis. They will be reconsidered in the summary.

At the end of Part Two some of the capabilities were presented of the administrative processes possessed by the Ss in the experiment. These information processing capabilities will be operationally explored and developed in the following presentation by first generating a simple administration process, then building upon it until the resulting sequence of transformations parallels that of the Ss. Protocol One will be used as the primary model for these operational studies.

By sequentially diagramming the state by state transformations of the First S, identified in the previous section, a relatively complete graph of his activities can be expressed. Figure XIV charts his behavior during problem solving and suggests which activities of design an operational description must be able to replicate.

Two elementary requirements that any minimally successful administrative process must provide are (1) a control that keeps the design process from trying the same configuration over and over again, and (2) a means for determining whether the process is moving towards a solution.

UNDIRECTED SEARCH

The simplest administrative process incorporating the first control would provide a set sequence of operations; 'first do this to this, then this to this, etc.' The sequence of transformations would be a priori determined. The system would proceed to its final operation, which would supposedly produce a solution. Such a sequence can describe the process by which a particular designer resolved a specific problem. It is essentially what has been done in this study thus far. But it is unlikely that designers themselves use such a set sequence for administrating operations. A different sequence of operations is needed for every problem encountered; a new problem could not be solved because its unique sequence had not yet been learned. A human designer's ability to generalize requires that his administrative processes include operations that can apply to a variety of situations. A state by state description of transformations does not vary according to information within the problem itself. It does not alter the process dynamically in response to information gained while processing. But it intuitively seems

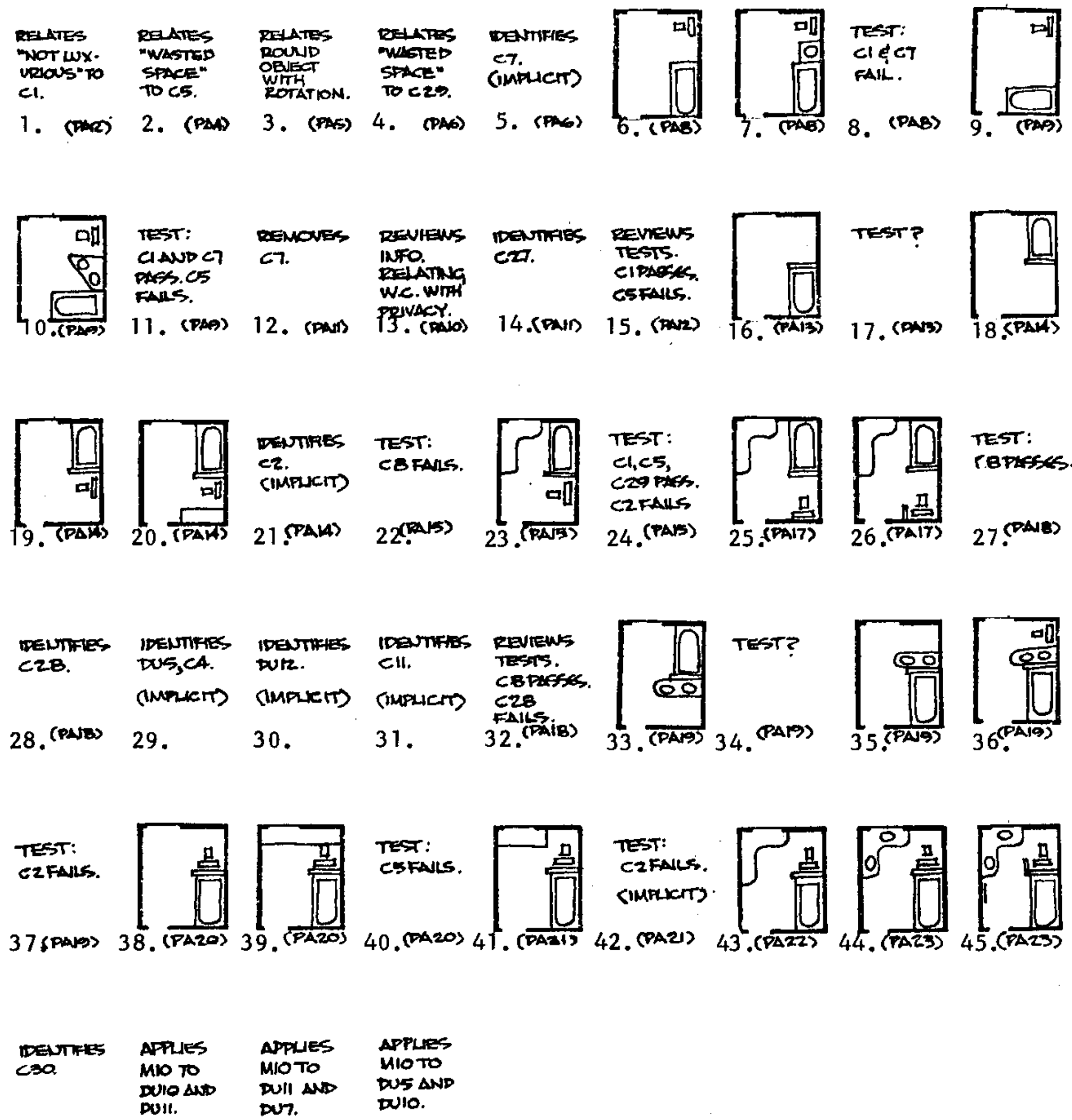

FIGURE XIV: State sequence expressed in Protocol One. The symbol in ( ) designates the protocol excerpt where each state transformation took place.

that man does - in order to determine the appropriate sequence of operations to find a solution, and to give direction to his search for a solution.

A slightly more complex system that includes a means for directing transformations towards a solution would be to sequentially order Manipulations and DUs. Each DU would be manipulated according to a priority sequence of Manipulations, testing after each operation to see if the constraints for that Unit had been fulfilled. If they were, the system would proceed to the next DU and repeat the sequence of Manipulations and tests, and would eventually include all DUs in a state that resolved all constraints. If all the Manipulations of the sequence were tried without positive results, the system would then regress to the previous DU and search for another acceptable transformation of it.

This administrative system would utilize information gained from previously solving similar types of problems to properly sequence the operations. The probable difficulty of finding an acceptable configuration for each DU would be incorporated into the predetermined priorities. Such a system would not generate again a total configuration that had already been rejected, but would follow a complete tree search where each branch node is a DU. The block diagram for such an administrative system is shown in Figure XV. Such a system incorporates intermediate goals that tell if a particular configuratory exploration is advancing towards a total solution. These intermediary goals are of the form "find a configuration for this DU that fulfills the constraints".

Such a system may be called Undirected Search and is capable of finding solutions to design problems. By determining the priorities expressed in

Protocol One for both DUs and Manipulations, and using its sequence of constraint identification, the hand simulation shown in Figure XVI was run.* It was generated by manipulating the same symbols externally represented in the protocol with the same set of operations, following the process shown in Figure XV. It produced a design in plan view that fulfilled the constraints identified in Protocol One. It is inefficient; it must try all counter locations, then all watercloset locations, no matter which constraint is unfulfilled. Even though no configuration is repeated that is exactly like any others, many obvious similarities are repeated. Its total number of operations is far greater than in any of the protocols. In general, little similarity exists between its process and those observed in the experiment.

In running such a simulation, several issues became significant. Because constraints are modified during the process, a good solution for the current definition of the problem may not be tried if repetitions are not allowed. They may have been eliminated earlier because of a constraint that is not now active. On the other hand, significant redundancies are injected if repetitions are allowed. Also, the system loses efficiency. The most efficient resolution of this issue and the one utilized throughout these simulations, is to allow repetitions between redefinition of a problem but not within a given definition. This amounts to suggesting that all processing prior to the final problem definition only contributes to problem identification; earlier solution generations are useful only as

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*For the method used in determining priorities, see Newell (1967,pp.53-114). Because the particular system developed here recycles manipulations for each DU and is thus hierarchical, priorities working at any particular level must be considered separately. Manipulation sequences taking place during a transition between DUs were thus not considered in the generation of this priority system. It was assumed that the priorities at such points automatically reverted to their original setting.

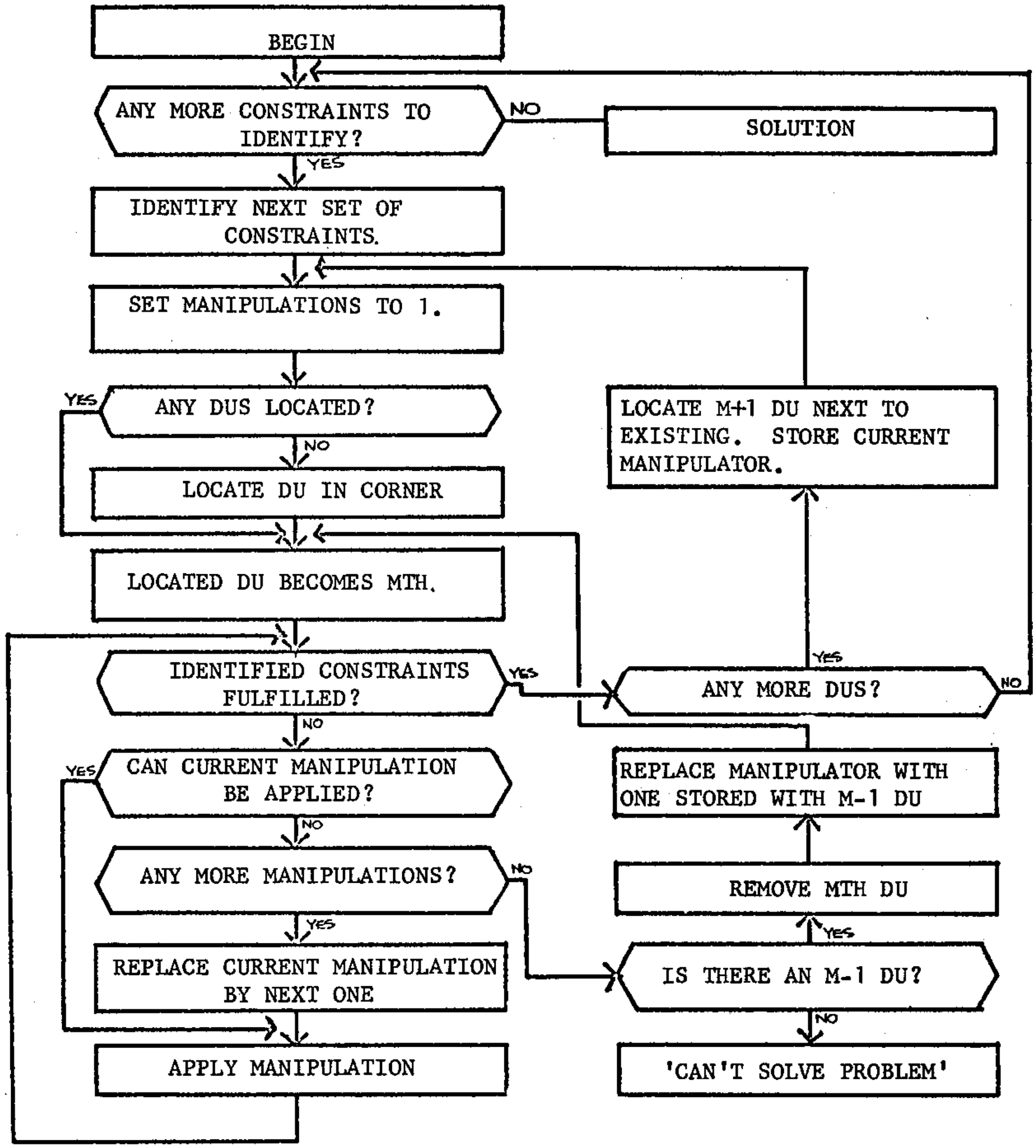

FIGURE XV. Block diagram for a Management Process relying on Undirected Search.

PRIORITY OF DUS: DU1, DU2, DU3, DU5, DU12.

PRIORITY OF MANIPULATIONS: M2, M3, M4, M8, M10, M11.

CONSTRAINT IDENTIFICATION SEQUENCE: (C1, C5, C7, C8, C29), (Removes C7), (C27,C2), (Removes C29), (C28,C4), (C11,C30)

FIGURE XVI. Simulation Number One. State sequence using Undirected Search. The constraint checks following each operation have not been included. If included, the sequence involves 139 state transformations.

cues for retrieving constraints and for allowing a variety of alternatives to be generated for consideration.

SEARCH HEURISTICS

Undirected Search possessed few of the capabilities identified earlier as being readily available to human designers. In the simulation certain manipulations, such as 'Locate above sink' were only utilized after all others had been exhausted. Yet the human designer was shown to go directly to this manipulation when the constraint 'mirror located in place of use' was identified. Thus his administrative system dynamically adjusted his processing in accordance with information gained during design.

One of the capabilities identified at the end of Part Two was the ability to use the information about certain kinds of constraints to select particular Manipulations. Such associations between constraints and Manipulations can be called Search Heuristics. A Search Heuristic assumes there is some specific transformation that resolves a particular constraint or appropriately deals with a particular DU. Their primary role is to delimit exploration. Such relations are heuristic because wider exploration may show that a constraint can be fulfilled in a variety of transformational states - some possibly original. It could be assumed that designers have several Search Heuristics for a DU or constraint listed in a priority. Only after the Search Heuristics have been exhausted would it be assumed that a designer resorts to the undirected search of the first simulation. Search Heuristics seem to be the typical means for selecting verbal attributes of DUs. Each Search Heuristic represents a possible means for a solution. Thus Manipulators such as M6, M8, M10, and M11 can be considered responses to Search Heuristics that are potentially relevant for only certain types of constraints. It is possible that the protocol of a S particularly familiar with a specific class of design problems, would have many DUs and constraints available for immediate recall and would rely on Search Heuristics for the majority of his operations. A designer with the most general capability would not necessarily be the most efficient for a particular problem type.

Identifying the Search Heuristics in a protocol requires careful analysis. It is possible to specify one for each action; the result would be the equivalent of a state transformation description. Certainly, a more limited set of heuristics is used by human designers. Those operations that are repeated and direct search in such a manner as to gain efficiencies can be considered Search Heuristics. Their final determination should be their generality, their usefulness in resolving a wide range of different problems. From the First Protocol, the following Search Heuristics relating constraints and Manipulations have been identified: C1 and C8 → M8 to DU2; C4 and C11 → M11 to DU5; C7 → M2 then M3 only, to all DUs; C27 → M8 to DU1; C30 → M10 to all DUs.

In Figure XVII, the first administrative system has been modified to utilize these heuristics. As a priority system of Manipulations may be confounded with Search Heuristics if considered together, priorities must be re-analyzed after removing those transformations attributed to Search Heuristics. The resulting transformations are shown in the simulation presented in Figure XVIII.

The major state sequence resulting from the inclusion of these heuristics is not different from the earlier one in the alternative schemes it explored. Yet significant efficiencies of processing were gained. The

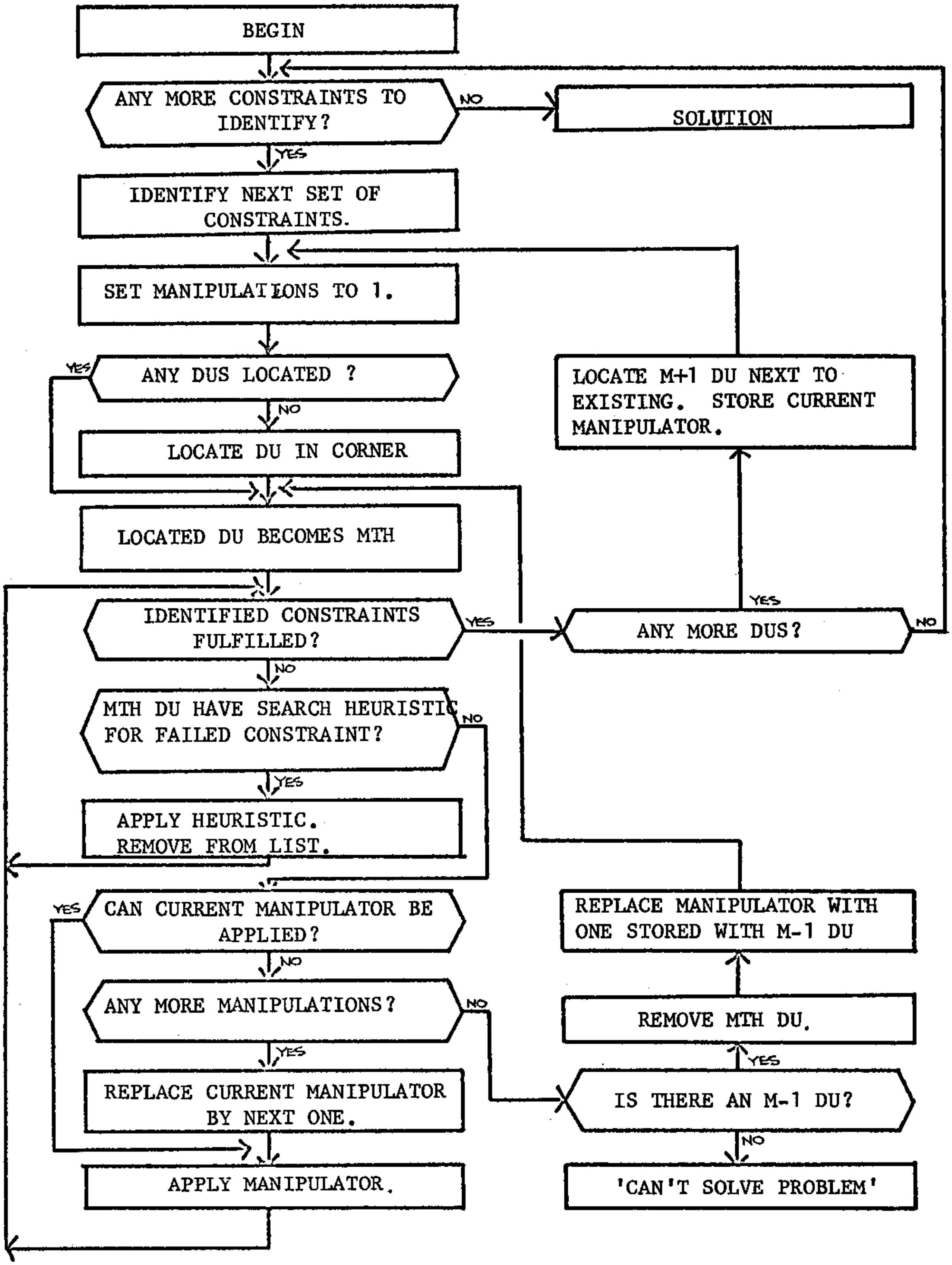

FIGURE XVII. Block diagram for an Administrative Process relying on Search Heuristics.

<u>PRIORITY OF DUS</u>: DU1, DU2, DU3, DU5, DU12.

<u>PRIORITY OF MANIPULATORS</u>: M2, M3, M4, M8, M10.

<u>HEURISTICS</u>: C2 and C8 → M8 to DU2; C4 and C11 → M11 to DU5, C7 → M2 and M3 to all DUs; C27 → M8 to DU1; C30 → M10 to all DUs. (For all DUs).

<u>CONSTRAINT IDENTIFICATION SEQUENCE</u>: (C1, C5, C8, C29, C7) (Removes C7), (Adds C27), (C2), (Removes C29, adds C4, C28), (C11, C30)

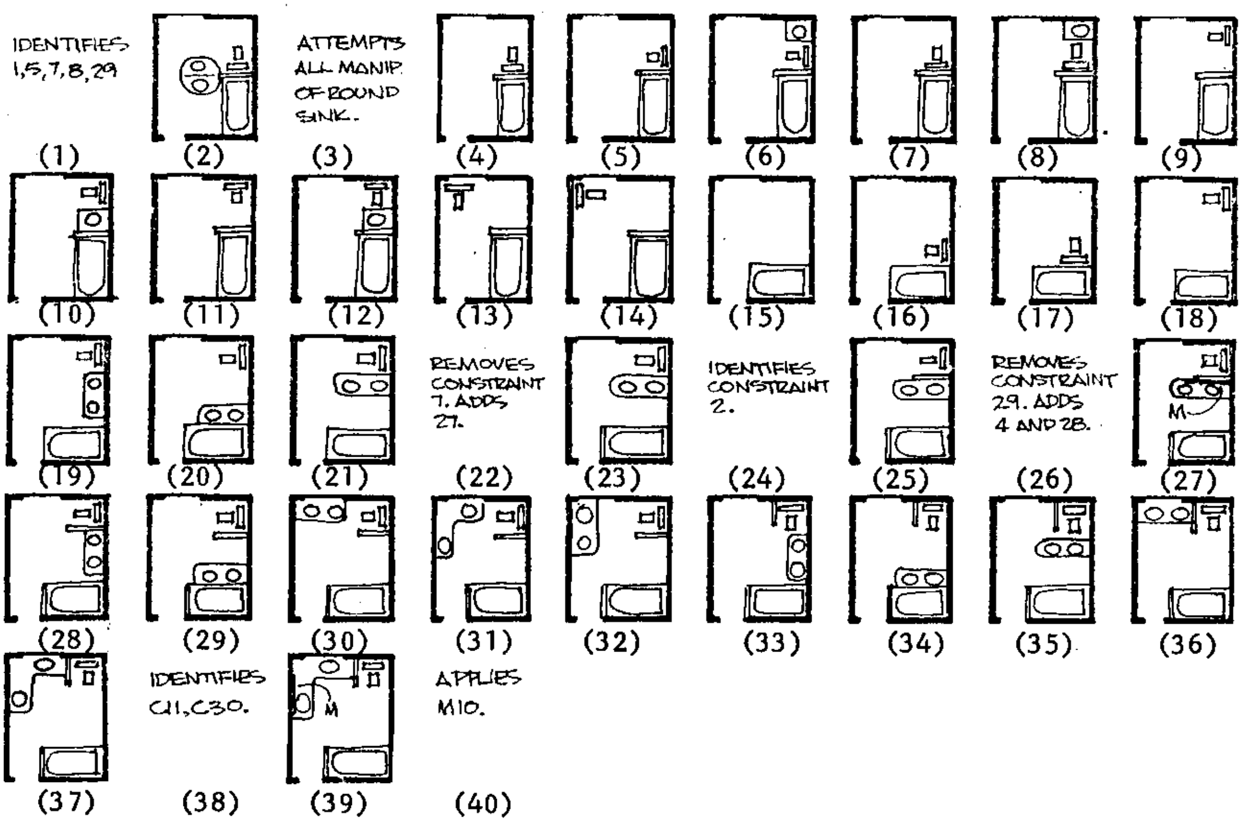

FIGURE XVIII: Simulation Number Two. State Sequence using Search Heuristics. Constraint checks following each state transformation have not been shown. The total number of operations here is 79.

system utilizing Search Heuristics was almost as efficient as the first. The value of heuristics thus becomes evident.

But to provide a reasonable duplication of Protocol One, more Search Heuristics must be included. Those required to reasonably duplicate the protocol's unique processing sequence are: all DU2 constraints →M3 first, then normal sequence; if all DU3 manipulations fail, go to the top of the DU priorities. (This rule is applied only after the first iteration.) By adding these Search Heuristics and processing again, the state sequence shown in Figure XIX is evoked. This sequence begins to replicate that of Protocol One.

The braces in Figure XIV designate those portions of the protocol which correspond with the simulation. Of significance is the similarity of the initial states generated while Constraint C7 was active ('plumbing on one wall'), the development of the same intermediate solution (27 and 26 in simulation and protocol, respectively) and the generation of a final solution only upon reiterating part of the total process. The simulation begins to reflect the procedural pattern of the Protocol. Yet the simulation still considers several alternatives never considered in the protocol, e.g., 16, 21 and 28. At the level of this study, it is difficult to determine whether the Protocol reflects not yet identified heuristics that cause these variations or whether some transformations can be considered "errors" based upon the S's cognitive load, and thus irrational behavior in terms of the S's own processes. It is not at all clear that even the heuristics utilized in this simulation enhance the resulting process, in speed or in generating unique solutions. In fact, all earlier systems could find the same solution with only one iteration of the process. This Administrative System required two.

PRIORITY OF DUS: Medicine cabinet, mirror, counter, watercloset, bathtub.
PRIORITY OF MANIPULATORS: M2, M3, M4, M8, M10
HEURISTICS: C2 and C8 → M8 to DU2; C4 → M11 to DU5; C7 → M2 and M3 only, for all DUs; C11 → M4 to DU 12; C27 → M8 to DU1; C29 → M3 first, then normal sequence for DU2s, and if a DU3 sequence fails, resort to top of DU priorities.

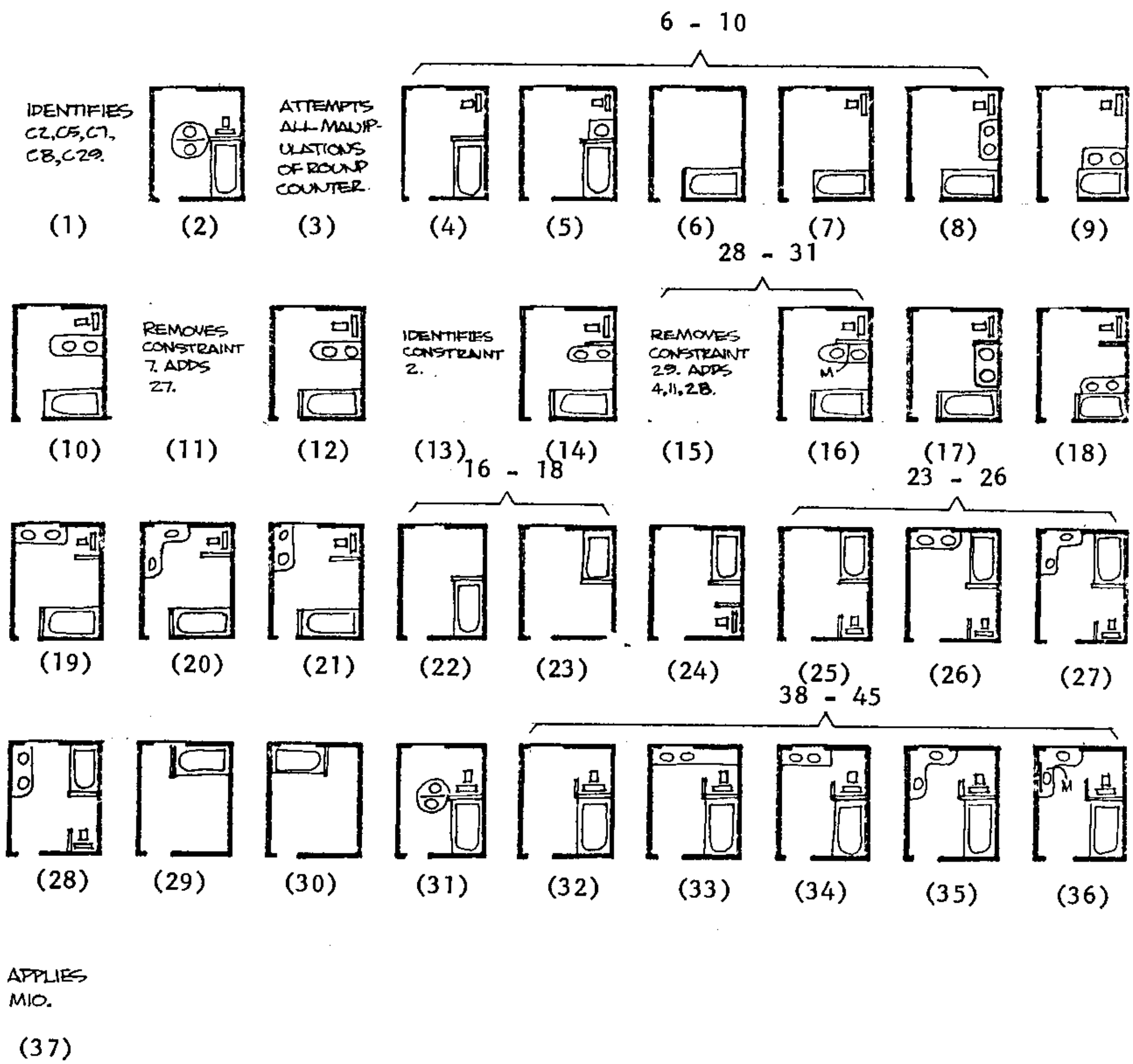

FIGURE XIV: Simulation Number Three. The state sequence of an allocation system, which attempts to duplicate Protocol One, requires 74 steps to reach a solution. (Constraint checks following each state transformation have not been included.) Braces designate the portions of the protocol which correspond with the protocol.

The three examples presented here, one Non-Directed Search and two examples utilizing Search Heuristics, introduce the role of administrative processes in design. Essentially, all administrative systems bring together the information about the design problem and solution processes, that is, Design Units, Constraints, and Manipulations. Two kinds of controls have been proposed. Priorities of Manipulations and DUs may be utilized so that more powerful operations are tried before others. Search Heuristics allocate particular operations that supposedly respond to specific situations. They may be evoked by either a particular constraint or DU.

It is clear that administrative systems play a significant role in determining both the efficiency by which a design process finds a solution and its power to find the unique solution that satisfies all constraints. Almost nothing is known about the associations that determine priority systems in Undirected Search. And while various authors have discussed heuristics, a review of the literature shows that the term has been applied to aspects of both problem identification and transformations.* Discussions of heuristics in problem identification deal with the significance of DUs and constraints to achieve particular but abstract goals. Heuristics applied during problem transformations direct search in particular directions. Future discussions of heuristics in design would benefit from utilization of this distinction.

Few additional gains would be achieved in evolving more complexly organized administrative systems and running hand simulations here. The capabilities of the First Protocol, if not its details, have largely been replicated. Those capabilities unique to the other protocols, hierarchical

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* See (Polya, 1945; Minsky, 1963; Eder and Gosling, 1965; Reitman, 1963.)

search, the utilization of a variety of representations, and the ability to utilize earlier generated problem states, have not yet been operationally described. But before efforts at generating mechanisms for replicating these capabilities are made, it seems worthwhile and indeed now possible to develop a general computer model allowing such simulations. From studies on such a model, detailed evaluation of various administrative systems, Search Heuristics, various constraint, Manipulator and Design Unit sequences, would be possible.

SUMMARY

What has been largely achieved is a hand simulation of an intuitive design problem solver dealing with an elementary design problem. A model has been developed that attempts to explain how at least some designers currently solve their problems.

The system and model of design offered here appears operational; they were capable of simulating human design efforts of at least a minimal level of difficulty. Protocol One, though not expressing the most sophisticated processing, was not the most simplistic. It involved a plan representation, mixed Undirected Search with Heuristics, and was able to resolve a large number of constraints. The simulations carried out thus far do not involve hierarchical design processes; Design Units are not themselves designed. This is one of the most interesting qualities of design problem solving. Only a machine would be patient enough to carry out such recursive simulations, yet it is a research area offering rich potential rewards. Such recursions may only require the appropriate structuring of DUs and separate representational areas in memory. Hierarchically organizing machine simulations may significantly enhance their "creativity".

At present, the system is conceived to work in only one representation. One of its disadvantages, when compared against human designers, is that it cannot manipulate the wide range of information that is within man's capabilities. A major improvement would be to allow it to utilize a variety of representations, and transfer information from one to another, as needed. This capability has been clearly expressed in the protocols. It is likely that other information processing capabilities are possessed by other designers.

In returning to the original description of design operations, the Generate and Integrate operations identified in the first report have been greatly revised and expanded in the examination of the present experiment. It was seen that the activity bringing together Design Units and Constraints does so by a complex process that in its most general description can be conceived as a generate and test operation (test then generate, in our case). Administrative processes are required to direct the Generate and test sequence. Some of those used by human designers have been examined.

The transformation sequence we have examined includes Identification of Constraints and Design Units, Manipulations of representations of those Design Units, and the application of constraints to configurations of Design Units. If major groupings of operations are to be defined, it seems then that these three, Identify, Test and Manipulate, are the ones to be considered. They essentially outline the operations needed to achieve the activities of problem identification, data gathering, analysis, synthesis, and evaluation - the activities previously used to describe design. Each operation is comprised of more detailed ones. Moreover, the administration of these activities is in itself a complex control problem with its own set of operations.

New issues for study have been identified from the protocols. The first one concerns representation. If languages are significant influences in problem solving, as was indicated, then informal languages such as graphics and iconic models should be quickly explored so as to determine their unique "grammatical" capabilities. This class of languages is uniquely context laden. No single constraint can be resolved without involving many other contextual decisions, particularly metric ones. Context free grammars for spatial design possibly would greatly expand the resolution powers of design. On the other hand, the contextualness of graphic grammars currently play a major role in helping the designer identify constraints. By requiring certain information to be expressed, a graphic representation encourages the identification of constraints relevant to that information. Also, if each representation or language also possesses operations that can only transform certain kinds of information, some subset of all the information that can be expressed in that language, then the analysis of different languages for their particular contributions as problem solving "tools" may be possible.

Another significant issue partially illuminated in this study is the structure of information used in design. This structure and information retrieval techniques for searching it are highly interdependent. The exploration of retrieval techniques for human memories has only been started. Yet this may turn out to be one of the most significant variables influencing creative design capabilities.

Last, this study has gained some insight into the unique capability of intuitive design. If the model developed here is representative, then the unique emphasis of intuitive design is its ability to include any kind of consideration into its process. Not limited to a formal model of the entity being dealt with, the process is not bound to a predetermined set of parameters. Any parameter can be evaluated that can be represented in a binary test. The unique context of a problem can be utilized in the generation of constraints. On the other hand, generate and test can only be considered a low level problem solving technique. Flexibility in structuring a problem seems to limit design to such relatively "primitive" techniques. The essential similarities and differences between engineering design, with its emphasis on formal analysis, and intuitive design, as carried out by most architects, are thus suggested. Both must specify their problem. But while the engineer relies on a formal model to identify relevant constraints, the intuitive designer directly retrieves these from informal verbal and perceptual descriptions of the problem. In achieving this flexibility of identification the intuitive designer places heavy demands on subjective memory. He is also forced to rely on a general but relatively weak problem solving technique.

The study reported here deals with one type of intuitive design. Hopefully, future studies will cover the whole gamut of design tasks providing a firm basis for a science of design methodology.

APPENDIX A

THE ORIGINAL NOTES OF THE DESIGNER

March 9th: 8:30 A.M. til 10:30 A.M. I read the program. 10:30 started to think about a module suited for office layout. First consideration a 3' by 3' module, this, however, does not result in the required products for floor spaces demanded in the program. As most of the spaces in the program are divisible by 30 square feet or can be adjusted to it without surpassing the $5^{o}/o$ limit of deviation demanded in the program, I propose a module which results out of a multiplication of 30 square feet. After talking it over with W. (boss) he suggests that I take an arbitrary 5' by 5' and start drawing up the areas required in the program. 1:00 P.M. I decide on general depth of 10' for the offices and draw areas up at one sixteenth of an inch to one foot. Work is done by 5:30.

ANALYSIS

1. Receives some design units and given constraints. Design units given are: rooms (which imply a location), other buildings, and site. Given constraints are: access required to rooms, room relationships, room areas, total area.
2. Identifies DU, structural module.
3. Generates an alternative for module. Attempts to integrate it with area constraints. (Unsuccessful.)
4. Identifies a common factor for area, which is a constraint for module.
5. Generates an alternative for module based on common area factor.
6. Integrates module alternative with area constraints.

THE ORIGINAL NOTES OF THE DESIGNER

March 10th: 8:30 A.M. I take a second look at site plan and try to think of an image which might stress whatever spatial and architectural amenities are hidden in this site and should be completed by this additional building and its extension. Having not much of building volume in regard to the site I think one should not try to compete with these office structures and the residential tower which are going to rise on the same site. The Town hall should expand and not rise; it should have at most three stories and it should look different from any other administrative building. I think of a hall which is covered by offices and rises like a little hill out of the site, roofspaces being used as terraces. 10:30. W tells me how he thinks it should or could look: U-shaped courtyard with city council hall somewhere up so that people might pass beneath it. Shows me P.A. competition for the Boston town hall; the second prize has about this shape. We both agree that the "other municipal building" and the "extension" should be located on the east side of the site. This side should become the area for parking and the Police should be accessible from there.

ANALYSIS

7. Identifies design unit, image. Searches for constraints relating image to site.
8. Identifies constraint, relative volume.
9. Relates number of floors (a design unit) with relative volume.
10. Generates an alternative for number of floors.
11. Generates alternative for image. Identifies DU, terraces.
12. Receives an alternative for image. This alternative includes constraints for building form and location of council room.
13. Generates an alternative for location of "other municipal building" extension, parking area. These alternatives seem to satisfactorily meet the relevant location constraints.

2:00 P.M. I try to draw up a flow pattern for the whole program at the scale of one thirty-secondth to an inch. The results do not make too much sense and we decide (at 6:00 P.M.) after W. has taken a look at it that the guy who dreamed up those relationships did not know very much of a town hall either.

14. Attempts to integrate alternatives chosen to date with access and room relationship constraints. Identifies conflicts.

March 11th: I start to fit program into rectangular shaped "floors" at 8:30 A.M. W comes at about 11:00 and shows me a sketch that he made after I had left yesterday evening, as it is v-shaped and split in the middle with the town hall on top. I become doubtful whether I could adjust functions of the program to such an entrance situation. I start coloring the different degrees of accessibility required in the program (on the flow pattern I drew yesterday), then I try to put different departments into floorplans until 5:30 P.M.

15. Identifies sub-unit for room location, floor level. Identifies design unit, floor shape. Identifies constraint "rectangular" for floor shape plus a total area and shape per floor as determined by chosen image alternative.
16. Receives further information on image alternative.
17. Attempts to integrate image alternative with access, and design units of floors, rooms and their location. Identifies conflicts.

March 12th: 8:30 I think of a section which could result from W's sketch in order to figure out the traffic in this shape. All the things which are considered in the program as having a need for very good public access I think should go on the ground floor. As W. thinks of the city council hall as something floating above the entrance lobby, this should go on top and the general office spaces should go in between. I try to get an entrance hall which takes care of this relationship between Finance and the Public works but after a whole day of trying I have to realize that it becomes always so complicated that it would flunk any competition because nobody would bother to understand such a complicated entrance situation. And even in reality it must be simple and fail-safe so that everybody finds immediately what he is looking for. I think back on townhalls that I know and I remember vaguely one by Aalto for a very small town. I should look it up in the library.

18. Identifies a constraint relating access constraints for room units with floor level design sub-unit.
19. By integrating existing constraints for floor level with room units and determining which room units are undecided and which floor levels still free, identifies probable floor level of remaining floor units.
20. Attempts to integrate access constraints with room unit locations. (Recognizes that constraint locating council room conflicts with constraint relating access of room unit with floor level.)

March 16th: Start at 8:30 A.M. and look at those books I got from the library yesterday; a book on the work of Aalto, a German publication about townhall competitions, a book written by a German but translated into English about office buildings. I took a good look at Aalto's little town hall and am impressed by its simplicity and refined humbleness. I show it to W. and he feels that we could learn a lot from it but he still insists on having

21. Looks for new alternatives.

council hall on top of any office structure. I argue that in regard to the good climate and the idea (his) of the u-shaped court-yard we should employ this yard as a mayor lobby in the open air and put city council chamber at the first floor so that all the traffic creates a lively thing in this court yard. He says O.K. I should start drawing up my ideas. I figure hall should be in the view axis of entrance steps. No lobby should be needed and entrance to the different departments should be from the court. Maybe the police should be on the west side of site to form the third wing of u-shape or it could be underneath entrance level accessible from east, and third wing should be second stage of building, which is just a landscaped wall in the first stage. I draw up those two solutions but they do not look too sexy. 5:30 - W. has left already so I cannot talk with him.

<u>March 17th</u>: 8:30 A.M. Try to draw those sketches of yesterday up to scale (one thirty-second of an inch equals one foot). If I put police on the east side below the entrance level of plaza I wind up with one half of department facing nothing but complete darkness and the other half looking at the parking lot. W. states the opinion that even cops do not deserve such a treatment and I have to agree. But he does not want them at the west side, so what? He says I should continue trying. I figure we should break the whole volume into two little fractions and give each department its own little pavillion with a patio - put the whole thing on a landscaped hill and achieve a dignified exterior by repetition of the same small elements rather than by long wings of office buildings. I start working on this solution. A pavillion 60' by 60' seems to work quite well - either I put a patio in or a skylight if more space is needed. I draw elevations.. they look like a supermarket or temporary army structures if I put any type of window at the outside. W. sees it and says we should put as little office space as possible on the ground floor because this will more or less always look small and seedy. He says we should put some of the volume on pillars. I say that we have to count any area covered by floor space as 50% of the floor space. He says he knows and he does not care because the thing that matters is not so much the floor space tabulation but how the thing looks. Leave at 5:30 P.M.

22. Identifies a change in image alternative that changes the constraint on the location of council room. This constraint does not conflict with constraints pertaining to access.
23. Identifies a constraint based on 'view' that locates council room.
24. Identifies a constraint relating image and access constraints.
25. Generates two alternatives for location of Police Dept. One alternative relates image with design unit, "future expansion".
26. Attempts to integrate these two alternatives with other room locations and image.
27. One attempt at integration conflicts with an identified constraint that all offices should have visual access to outside.
28. Generates a new alternative, a series of pavillions, for image that involves a completely different set of constraints.
29. Generates a module alternative that integrates well with new alternative image.
30. Generates alternatives that allows new image to be integrated with room area constraints.
31. Attempts to integrate new image alternative with other constraints and alternatives. Identifies conflicts.
32. Identifies a constraint relating pedestrian-scale image (a design unit?) with room units on first floor.
33. Receives a constraint determined by image, possibley a refinement of previous image alternative. Relates this constraint to given definition of total area constraint.

34. Receives value for the priority of constraints; constraints determined by image have priority over area constraints.

March 18th: I start at 8:30 and try to figure out a new scheme. It is terrible there should actually also be an access from the parking lot, but always there is this police volume in my way. One cannot put it on pillars because it should be accessible - one cannot dig it into the ground because people work there all day long. I am spinning my wheels and do not get to draw anything up to scale. 4:30 P.M. W. comes and we try to figure it out together. W. ends up with putting police at south side of site accessible from the plaza. Image looks now like sketch. He tells me to draw a preliminary tomorrow just by drawing up floorspaces and leaving out partitions just putting in circulation nodes.

35. Abandons pavillion scheme as an image alternative. (Goes back to original image alternative of wings around a courtyard.)
36. Attempts to integrate original image and alternatives with certain access constraints. Location of Police Dept. produces conflict. Two alternative locations for police conflict with either access (given) or visibility to outside (self-imposed) constraints.
37. Receives new alternative for Police Dept. location. This alternative fulfills all constraints identified to date.

March 19th: Start to draw preliminary. First assume a module of approx. 15'. (A structural bay) Second assumption I still would like to have those terraces of the first ideas I had. I put circulation in the middle of police and financial wing. W. thinks this is confusing and wants entrance rather at the gap between those two. These complimentary angles at this corner give me hard time in designing a vertical circulation unit with w.c; spend whole afternoon looking for a solution.

38. Identifies design unit, structural bay. (This replaces the design unit, structural module?)
39. Identifies a further constraint for image. This constraint involves the inclusion of a new design unit, terraces.
40. Generates an alternative for location of entrance to each building (a design unit). Alternative conflicts with image constraints (?).
41. Receives new alternative for entrance location.
42. Attempts to integrate image, floor level, access, entrance location, room location, alternatives with a location of vertical circulation and public facilities alternative.

March 23rd: Found a sketch of W. on my table, he says it is about to scale (32nd) and I should try to keep the proportions of the elements (wings of building and plaza in the middle). I try to develop construction module of 16' (which fits the width of the wings as he sketched them, 1st floor 48', 2nd floor 40', 3rd floor 32'). In his sketch he indicated the emergency stairs on the end of the wings as being spanned between two load-bearing walls. I try to make a main structural element out of these load-bearing walls, which are approximately 8' apart and 16' long, by using the necessary elevators, 2.c. and stairs of the building and wrapping them in such an element. If

43. Receives a rough integration of alternatives and constraints. This integration gives structural bay width and location of vertical circulation.
44. Identifies structural system (a design unit that includes structural bay width and all structural constraints. Attempts to integrate chosen alternatives to date with a structural system alternative.

I would get floor plans working with this structure it would look quite good (we do not have to build a model for the competition, so I figure plans should look very ordered or even ornamental in order to promote interest of jury. This 45^{o} entrance was my work in the afternoon (starting 2:30 P.M.). How does this look and how should it look connection of cantilevering 3rd to protruding 2nd. Figure out several possibilities and do not like either one of them (but maybe I am biased - I never liked bitten-off corners and I regard it as a sign of utter mannerism - all of Milanos post war architecture has these baroque fractured edges - but who am I that I try to sell Dutch-Danish-Finnish cubes in the land of Yamasaki and Stone.)

March 24th: Took a second look at the floor plan, the whole business with the two load-bearing walls does not make too much sense from the point of view of circulation and functional layout. I talk it over with W. and he ways I should start laying out offices and other areas in those shapes which we have decided upon and I should not bother about the construction at the moment. He says he wants to see preliminary drawings as soon as possible and he does not care whether many problems remain unsolved. He shows me his preliminary drawings of the Berkeley art center (W. was finalist) and explains that he drew them up without really bothering too much just for the purpose of seeing that the whole thing looked like if rendered nicely and in order to find out which portions of the design were still vexing the eye and "illogical". Also to make first decisions of the future technique of rendering the final drawings for the competition. (This is a way of procedure totally new to me; I always figured the whole thing out without preliminaries and did not start to draw until everything was at least settled in one way.) As I draw things up I realize that this (his way) might have some merit because I am forced to make so many arbitrary decisions while drawing the plans that it is like a major brainstorm. I start with the Police Department which we decided should be on the ground floor of the south wing - then I try to figure out the finance and public works department in the west wing. I try to think of a council hall. I think it should resemble a Greek theatre and not so much a cinema (W. Netsch University of

45. Integration of rooms and floors with structural system alternative conflicts with room relationship constraints.

46. Told to ignore structural system constraints. (!!!)

47. Integrates alternatives to date, adding some alternative for every design unit so as to produce a first "complete" solution. The internal design of each design unit is completed. It is assumed that each of these involve a micro-process similar to the gross one reported in the protocol. (Implies a procedure of locating certain DUs before others.)

Illinois comes into my mind). As I draw the rows of seats I start wondering what kind of a shell I could wrap them in. It would be nice if these people could have their discussions in natural daylight - skylights should go all the way around the building fitted between u-shaped concrete profiles which also go all around and become thicker and higher the wider they span. I start working on the second floor of the west wing public works the lobby of the employees (which I always save for stuffing big holes in the actual vs. the required floorspace) and the personnel department go onto this floor. The long southeast wing of the second floor is using up all the floor space I have and I cannot find anything to put into those two third floors over the entrance. I stop to work at 10 P.M. and go home. At home I try to read but I am too tired and so I just keep on thinking of this townhall after having written the previous report.

48. Identifies DU, interior room design.

49. Integrates internal detail with "external" image.

50. Continues integrating alternatives. (Indicates a conflict in some alternatives he has chosen and the constraints determining floor levels.)

March 25th: I start all over. Yesterday after I got home I thought of a different arrangement of the various departments and also of putting the circulation node back into the volume of all three floors. Also, I have come to the conviction that the police should have two entrances, one for the chief, the classroom and the conference room, and one to watch commander and the whole cop stuff which is basically very unattractive and which has to be open 24 hours a day. I put the purchase, the finance and the water (E 16) in the first floor of the west wing attorney and the rest of the public works except E 13 being linked to E 16 by a little winding staircase in the second, the third floor becomes a drafting room E 13 and F 8 as well as E 5 and 6 half of E 15 and all of F 11 go up there. The southeast wing now houses in its second floor the Mayor (B), his office is fitted in one of those odd shapes at the entrance, the City Manager, the personnel department, the rest of the planning, the building and fire prevention and the recreation. To work this scheme out I take all day long because it's much squeezing and juggling if I want the proportions of the building to stay like on W. sketch (actually I think one should not stick to this decision too much but W. is sort of very stubborn in this respect.)

51. Chooses other alternative concerning room locations that better meets access and room relationship constraints.

52. Identifies a design unit (or alternative?) that responds to the circulation constraints within the Police Department.

53. Integrates room locations with other constraints and chosen alternatives. (Describes a process of squeezing and juggling certain units to fit an overall form.)

March 26th: I start drawing the plans up in ink (scale 32nd) all rooms are in the plans; try to think of elevations and start with sections after having decided that the surplus area in the north part of the eastern wing under which the city council hall is located should be used as chimneys for skylights. I try to do some graphics with the "pavement" of the plaza (I would like it to develop in concentric circles starting from the Council hall but it does not look too good and I just use the idea for the entrance situation (sketch and leave the plaza in orthogonal orientation.

54. Generates a more detailed specification of the integrated alternatives to date. In so doing, begins thinking of another design unit with its set of constraints.
55. Identifies alternative for DU to facilitate integration of alternatives.

Wednesday, March 30th: Today was Facade day. Started with the south elevation, facing Sonoma St. Scale 1/32. Decided on a height of 14 feet from floor to floor (e.g., roof) and on Attika height and balustrade height of 3 feet. After sketching for two hours with various fenestration patterns (regular slots, irregular slots, L-shaped slots, sunshades protruding, windows set back, sunshades incorporated in balustrade, I decided on drawing one up to scale. Result: looks really different from what I hoped it would like. Start sketching again. Proportion of first floor to second and third should be different; first floor 16 feet high, second and third 12 feet high. Looks better if fenestration is irregular because it really does not matter so much and if it is irregular it will best fit with those plans. The slope at the east end is quite a problem. I draw east elevation - the Council chamber does not look too bad but something is too square about it.

56. Considers design unit, facade. Generates an alternative for floor to floor distance. (Based on proportion?) Generates an alternative for height of balustrade (for same reasons?).
57. Generates various alternatives for design unit, fenestration pattern. (This design unit is a sub-unit of facade.)
58. Integrates one alternative with rest of solution. (Is rejected.)
59. Generates new alternatives for floor to floor distance. (Why?)
60. Rejects an earlier applied constraint relating to fenestration pattern.
61. Site interacts with facade. (How?)

Thursday, March 31st: Showed those sketches to W. He said that I should start out in a bigger scale and that I should try to keep the appearance of the facades similar to those on the 32nd scale. At 10 I start to draw up the Sonoma Street side in two versions and I finish at two to go to Berkeley and see my dentist again - a man can't be creative and toothaching at the same time.

62. Generates two alternatives for facade (it is assumed that they both integrate with other alternatives).

Friday, April 1st: Talk things over with W. He says he likes those slots on sketch and that I should try to make something concerning the whole building out of it - sort of a general theme. (O.K. let's make that thing real slotty and put some good concrete Jazz up on top at the same time accentuate the horizontal direction; these are the thoughts

63. One partially complete facade alternative receives approval.

I have while drawing up the East facade. My first attempt is to try the scheme of some Swiss architects (Studio 5) with that very thin concrete apron hanging down and leaving horizontal slots which turn the corners so making the roof apparently float and really stressing the horizontal. W. says that Calif. is not Switzerland and that I better get some real sunshades before my windows or everybody will be grilled in this thing. (Leave those slots and let's make it nice and shady, working slogan "mushrooms in the magic climate".) I really like the facade now; W. has already gone home; well I hope he likes it, too.

64. Applies a detail alternative (he once saw) to accepted facade alternative.
65. Detail alternative rejected. Identifies sunshade constraint to facade alternative.
66. Generates a combination of alternatives that fulfills his constraints concerning facade.

<u>Saturday, April 2nd</u>: I start again with Sonoma St. elevation. Now there they, or rather, we, have those roof terraces, so better show them also from the inside. The whole thing should be as calm as the east facade and the proportion of the elements should be the same although the elements should (because of the terraces) be different. I start out with horizontal element 3 by 8'. Piled one upon the other, it works out quite well. Three feet table height, between 3 and 6' you can look out doors to terraces would have a height of 6'4" and the panels would be either glazed or filled; the frames are out of concrete (prefab). W. sees this thing and says it looks like a factory. Has he ever seen a factory, I ask him? - he says if never, then now by looking at this "monotonous monster". O.K. let's make it cute (work slogan for the next one). I turn some elements into wall aprons rising from the ground letting this strip of windows continue on top. W. says it's looking like a mental institution, much too calm and really meant to upset nobody. I should make it look more like sculptured out of concrete instead of creating the impression of economy stucco. So working slogan for the next one "Squashed Wursterhall" - render it in pencil and W's idea of the Mayor's office being distinguishable in the facade (Work slogan, Eyelids for the Mayor). W. likes it and says I should leave out trees if I cannot do better than this "swarm of locusts".

67. Identifies facade constraints that relate one facade to another.
68. Generates an alternative for facade panel that fulfills his constraints.
69. Integrates internal view, fabrication process, with certain alternatives.
70. Receives a negative reaction based on certain visual associations.(?)
71. Generates new alternative for detail of facade.
72. Sum of facade alternatives rejected again for associational reasons.
73. Receives a constraint relating some facade detail alternatives with material. (When was material decided?)
74. Receives a constraint relating some facade detail with room location.

<u>Tuesday, April 12th</u>: Was on a trip to the Grand Canyon, but nothing has changed in the office when I come back. Draw up the other three facades with "Squashed Wursterhall" motifs, real dark shadows and comfort myself

75. Integrates alternatives to date.

that every wallspace I close does not mean total darkness inside because of rooflights which I hide behind that balustrade. W. says the Council chamber looks square from the east side. Let's make it asymmetrical (works better in plan, too).

76. Receives a constraint relating facade dimensions (proportions).

Wednesday, April 13th: Start to readjust plans to facades at 16th scale; these 45° angles at the entrance are making life complicated - no room seems to make sense in this corner if it is smaller than 500 square feet. So I put the class of the police department in one and the accounting finance in the other. I wish we had spent more time discussing the construction of this building. No matter where I put those columns, they look like somebody forgot to have them taken away. I go back to square columns - does not look too bad, but W. rightly claims that people would wonder about the facades after looking at those Miesian plans. Let's make slabs instead of columns and try to make the exterior walls as concrete-like as possible without commiting yourself to openings (W. instructions for the next one). After seeing the next one we decide that that still is not it but slabs are "in". The exterior walls should be traced with two thick lines, leaving a little white line in between - no doors should be shown - column-slabs should be flush with exterior and protrude a little bit into the interior.

77. Integrates alternatives to date. (Identifies a relation between size of room and integration with part of building shape.)

78. Integration of structural system with other alternatives conflicts with certain symbolic constraints concerning image of drawings.(!!)

79. Generates another structural alternative that meets above constraint.

80. Structural alternative generally accepted.

81. Structural system is integrated with alternatives on floorplan while respecting an image of the drawing constraint.

Thursday, April 14th: I draw up the whole floorplan in ink as if it was on the boards. Pave the courtyard with a regular pattern of rectangular double squares 3' x 6' going in order to avoid confusion at these rotten 45° angles at the entrance. W. is on a business trip and won't be back before next week.

82. Generates alternatives for some remaining design units. Further integrates various details. (It can be assumed that a unit like the courtyard is generated by the general process of identifying possible subunits and integrating them while respecting various constraint relationships. In other words, it is a repetition of the overall process at a smaller scale.)

Friday, April 15th: Draw up second floor and put a bathroom for the Mayor and the general office of the City Attorney in those 45° angled walls plus a duct shaft. Take first floor again and enlarge the area in the back of the courtyard to a full two-thirds of the plaza and make a pool with sculptures out of it and a bridge leading over it to those civic things which are proposed on the north end of the site. Before he left W. told me to think of some special "sales features". O.K. - "city hall with swimming pool".

Saturday, April 16th: Drew up the site plan with shadows and parking. Two hundred parking spaces for this thing. Well, I always knew that something was in the program to make this thing look like a supermarket. That's it. I try to put lots of trees on the parking lot. I try to indicate grassy lawns and brickpaved roads. Everything I do looks much too busy and sort of wrecks the whole thing. Besides this plan of the future development in the north is wrong, at least from a point of view what I have as site at 30th scale. Those fellows there assumed a much bigger lot for themselves than they are entitled to.

83. Continues integrating various design units.

Wednesday, April 20th: W. has tackled site plan and says we should ignore that "imposturous mess" in the north and show our plot and nothing more on the site plan, indicating slightly their Axis where it suits us. I draw up site plan again - takes the whole day.

Thursday: I go on the boards - start with 1st floor and basement which I designed while drawing it up in pencil. W. "nobody is going to look at this basement anyhow; for Pete's sake keep it simple". Basement looks pretty- it is only a couple of squares, lettering will bring some sense into it.

Friday: Second floor and third floor on the boards.

Saturday: Facades on the boards outlines.

Sunday: Rendering facades (pencil rendering takes such a long time and drawing on boards is slightly medieval, to say the least).

April 27th: Found note of W. saying I should add some stuff (trees and pavement and darker shadows to the site plan; spent whole day, til 5 P.M. to get this done.

April 28th: Started on perspective and spent the whole day looking (drawing again and again) for the best angle to look at this building started with viewpoint down on Santa Rosa St. The facade disappears behind the balustrade of the terraces. Go up the front stairs directly on plaza level, terrible distortions.

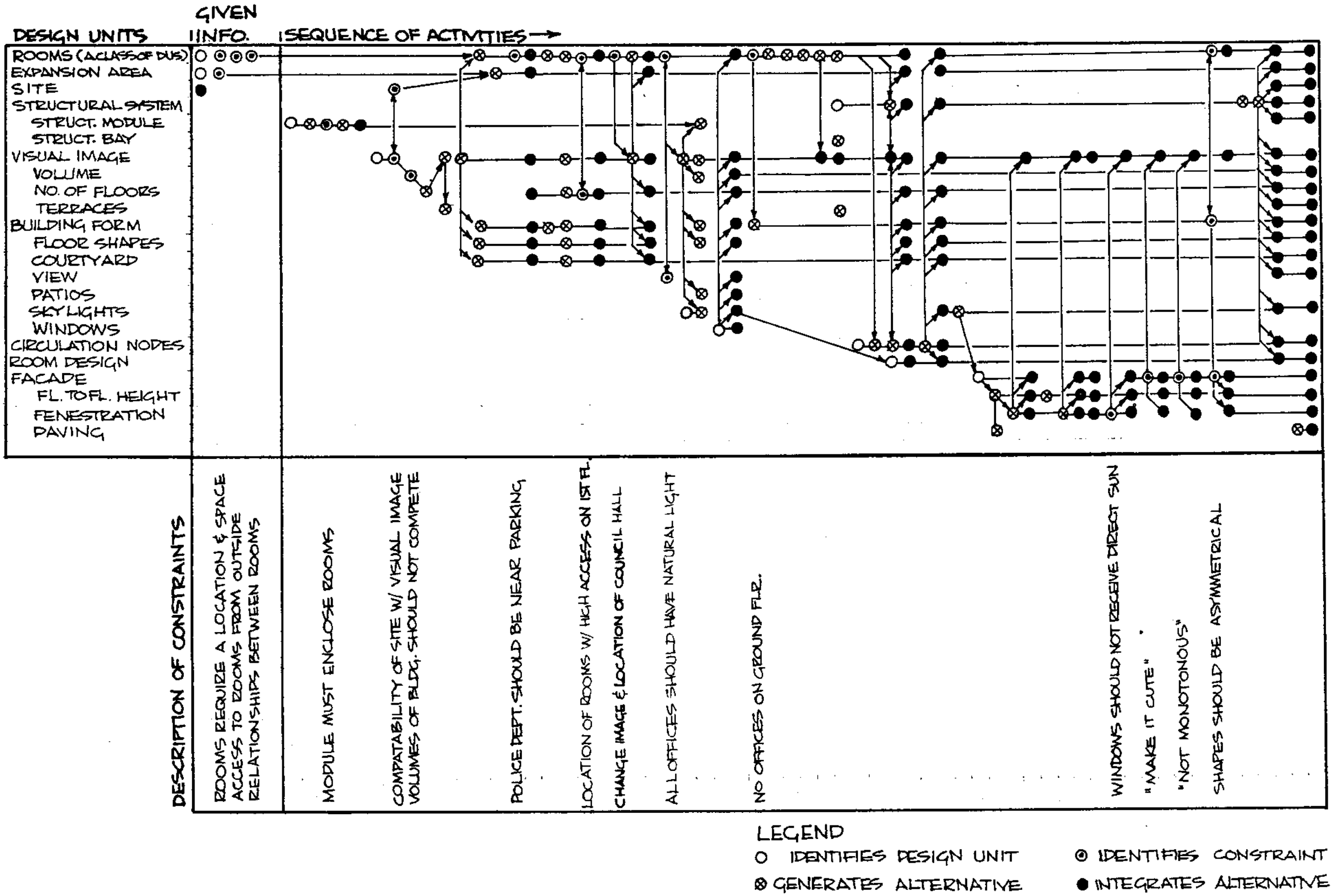
April 29th: Perspective looks like hell (W.). I make proposal to show inner court, using only one vanishing point. W. says it's all right, I should try it. Draw this view on up and it turns out to look quite nice. Council chamber and pool reflecting the building above. But W. and I agree that they will wonder why we have not shown the outside of our building. I say I feel much safer now with one perspective that can be drawn up to try the entrance situation next week.

May 4th: Perspective: took viewpoint way out and 28 feet above the ground (although it says in program normal eye level) and perspective turns out to look O.K., a little bit too small. I try it with a different picture plain show it to W. and draw on the board.

May 5th: Render shadows in perspective and turn it over to W. to draw people and trees and sculptures at the indicated places. Start to recalculate area for diagram. Turns out to be too big. Change measurements a little bit deducting one and a half foot in the width of each wing: O.K. 47990 (4800) maximum. Draw it on board and the work is done.

84. Total area constraint not fulfilled.
85. Modifies alternatives to date to fulfill constraint.

May 6th: Go to Santa Rosa with W. We look at the site and figure after we have turned in our stuff in the old city hall that they definitely need a new one and that we have a good chance of winning.....



ACTIVITY GRAPH OF CASE STUDY REPORT
CIVIC CENTER PROJECT

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13. ABSTRACT

Intuitive design, as carried out by architects, product designers, and some engineers, is analyzed as a problem solving task within the framework of an information processing theory of cognition. A study of intuitive design processes was carried out utilizing four protocols as experimental data. Two of the protocols are presented in this report in their entirety. From the protocols were identified the information used, the transformations carried out on the information, and some of the administrative processes directing particular sequences of activities. Analysis of the protocols led to an operational model of design and hand simulations largely replicating one protocol. Fundamental issues of design methodology are outlined. Of particular interest is the insight offered into semantic memory retrieval processes utilized by designers and the representational languages used in complex problem solving.

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